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DECEMBER 1914

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ON THE DISTRIBUTION OF ECLIPSING VARIABLE STARS IN SPACE

By HENRY NORRIS RUSSELL and HARLOW SHAPLEY

When the elements of an eclipsing binary, and its observed magnitude and spectral type, are given, it is possible to make a very fair estimate of its distance. Since the photometric data give the relative brightness of the components, the stellar magnitude m which the brighter star of the system would appear to have if it stood alone can be found at once. If we can estimate the absolute magnitude M of this star, the parallax π may be found from the relation

$$M = m + 5 + 5 \log \pi \qquad (1)$$

Kapteyn's definition of the absolute magnitude, corresponding to a parallax of $0''.10$, is here used, so that the sun's absolute magnitude is about 4.75. If the radius and surface brightness of the star under consideration, in terms of those of the sun, are R and J, we shall have

$$M = 4.75 - 5 \log R - \frac{5}{2} \log J \qquad (2)$$

(The logarithms here, as elsewhere in this paper, are common logarithms with base 10.)

The elements of the eclipsing system give us also the ratio r of the radius of the brighter component to the mean distance of the

components.[1] If the mass of the system is 2μ times the sun's mass, and the period is P days, the mean distance, taking the sun's radius as unity, will be

$$5.29\, P^{\frac{2}{3}}\, \mu^{\frac{1}{3}}$$

and we may write

$$R = 5.29\, r P^{\frac{2}{3}}\, \mu^{\frac{1}{3}}$$

Setting for brevity

$$5.29\, r P^{\frac{2}{3}} = A \tag{3}$$

we find

$$M = 4.75 - 5 \log A - \frac{5}{3} \log \mu - \frac{5}{2} \log J \tag{4}$$

The quantity A may be derived from the known elements of the eclipsing system.[2] The last two terms are usually unknown; but their probable values may be estimated if the spectral type of the star is known.

Consider first the surface brightness J. This is probably very closely related to the color-index of the star, and hence to its spectrum. There are two ways in which this relationship may be determined quantitatively with tolerable accuracy.

(*a*) On the assumption that the stars radiate like black bodies, the difference of surface brightness between any two stars (in stellar magnitudes) should be very nearly equal to the product obtained by multiplying their relative color-indices by the ratio of the mean effective photographic wave-length to the difference between the mean effective visual and photographic wave-lengths. From Parkhurst's data,[3] it appears that this ratio is about 3.8 in the case of the system of color-indices now in common use, based on extra-focal photographic work.

This method may, however, be expected to give somewhat too large values for the difference of surface brightness, for it is very

[1] This is called r_b in the table of elements (*Astrophysical Journal*, **38**, 162, 1913), to distinguish it from r_f, the radius of the fainter component. This distinction is unnecessary here.

[2] The density assigned to the brighter component of each system in the table just referred to is equal to A^{-3}.

[3] Russell, *Science*, N.S., **38**, 646, 1913.

probable that a part of the photographic faintness of the redder stars arises from increased intensity of both line and general absorption in the region of short wave-lengths.

(*b*) An attempt to determine the relative surface brightness of stars of the different spectral classes in quite a different way, by comparison of data obtained from visual and eclipsing binaries, has recently been described in some detail by one of the writers.[1] It gives results only for the whiter stars, but these should be of considerable accuracy.

As regards the mean masses of the stars of the various spectral classes, the principal data may be summarized briefly as follows:

(*c*) For 12 spectroscopic binaries of Class B, with both components bright, the mean mass of a system is 16 times that of the sun. There are good reasons to suppose that the methods of observation have in this case favored stars more massive than the average.

The mean mass of 8 visual binary systems of known parallax, and spectra A to F5, is 4.5 times that of the sun, and that of 10 systems of spectra F8 to K is 2.0. The few spectroscopic binaries of these classes whose actual masses can be determined give results of the same order of magnitude.

(*d*) A determination of the mean masses of binary stars of the various spectral classes, based on the data for more than 550 stars, on the assumption that the brighter components of these double stars are, on the average, equal in brightness to the mean of all stars of similar spectral type, is given in the paper already referred to. The brighter and fainter groups (giant and dwarf stars) among the redder types appear to be of different mass, and are treated separately.

The results of these various determinations are summarized in Table I. The second line gives the relative color-indices for the various spectral classes (taking for the moment the sun as a standard); the third, the values of the surface brightness in stellar magnitudes (i.e., of $-\frac{5}{2}\log J$) deduced from these by method (*a*); the fourth line, the independent results of method (*b*); and the

[1] *Popular Astronomy*, **22**, No. 6, June-July 1914.

fifth, the values adopted for the purposes of the present discussion. The next three lines give the values of $-\frac{5}{3}\log\mu$ derived

TABLE I

Spectrum	Bo	B5	Ao	Fo	Go	Ko	M
Color-index	−1.02	−0.88	−0.71	−0.41	0.00	+0.45	+0.91
$-\frac{5}{2}\log J$							
Method (*a*)	−3.9	−3.3	−2.7	−1.5	0.0	+1.7	+3.4
Method (*b*)	.....	−3.2	−2.0	−1.1	0.0	.....	>+2.5
Adopted	−3.6	−3.0	−2.3	−1.1	0.0	+1.2:	(+3.)
$-\frac{5}{3}\log\mu$							
Method (*c*)	−1.5		−0.6		0.0		.....
Method (*d*) Giant stars	−0.8		−0.6	.....	−0.8	−0.3	−0.3
Method (*d*) Dwarf stars	.....	.....	.....	−0.1	+0.6	+0.9	+1.2
Adopted	−1.1	−0.8	−0.6	−0.3	0.0	0.0:	.....
$4.75-\frac{5}{2}\log J-\frac{5}{3}\log\mu$ Adopted	0.0	+0.9	+1.8	+3.3	+4.7	+5.9	.....

from the discussions referred to under (*c*) and (*d*), and the following line the adopted values. Finally, the last line gives the adopted values of $4.75-\frac{5}{2}\log J-\frac{5}{3}\log\mu$ for each spectral class. If we call this quantity Q, then we have for any star, by (4),

$$M=Q-5\log A$$

With regard to the accuracy of the adopted values of Q, it seems probable, on the showing of the table, that they are usually within half a magnitude of the truth. Differences from the mean mass and surface brightness will cause larger deviations in the case of individual stars; but the probable magnitude of these deviations may be at least roughly estimated. For the 28 visual and spectroscopic binaries mentioned under (*c*) above, the differences between the individual masses, as derived from observation, and the means for the various groups correspond to an average deviation of ± 0.53 in $\frac{5}{3}\log\mu$. This includes very considerable effects of errors of observation, so that the real deviations must be decidedly smaller. The deviations of the surface brightness of individual stars from the mean for their spectral classes may be estimated

from the similar deviations in color-index. According to King,[1] the average observed deviation in color-index is ±0.086 mag., including the effect of errors in both the visual and photographic magnitudes. Multiplying this by 3.8, we find ±0.33 as the corresponding deviation in $\frac{5}{2} \log J$, which again, for the reasons just stated, is probably too great.

It would therefore appear that, for stars whose spectral class is accurately known, the average deviation from the mean values of Q can hardly exceed ±0.50 mag.—which corresponds to an error of about ±25 per cent in the estimated parallax. For faint stars, whose magnitudes have not been photometrically determined, and whose spectra can be only roughly classified, the errors may of course be much greater.

The stars whose parallaxes and distances are here estimated on the above principles are the 90 eclipsing variables for which elements have so far been computed. The elements of 86 of these have been published by one of us;[2] the others are added from later computations. Full details regarding all of these will appear in a forthcoming number of the *Contributions from the Princeton University Observatory*, and therefore only the essential facts are presented here.

Table II gives for these 90 stars (1) the name; (2) the magnitude m of the brighter component, obtained by correcting the observed magnitude of the system for the light of the fainter component. Magnitudes given in italics are photographic, and have been corrected for color-index in the ordinary way before the computations were made. Column (3) gives the spectral class, as determined at Harvard (except for the values in parentheses, which are rough estimates made in the manner explained below), and column (4) the quantity A derived from the elements of each system by means of equation (3). The elements computed on the assumption that the star-disks appear to be darkened at the limb have been used in all cases except that of X Carinae (for which they were not available); and in the case of ellipsoidal stars, the

[1] *Harvard Annals*, **59**, 175.

[2] Shapley, *Astrophysical Journal*, **38**, 162–168, 1913.

TABLE II

(1) Name	(2) m	(3) Sp.	(4) A	(5) λ	(6) β	(7) 1000 π	(8) R	(9) $R\cos\beta$	(10) $R\sin\beta$
U Cephei	6.9	A	2.15	91°	+19°	4".4	750	710	+ 240
RZ Cassiopeiae	6.5	A	1.88	100	+ 9	6.0	540	530	+ 85
β Persei	2.3	B8	2.57	116	−14	26.2	125	120	− 30
RT Persei	10.8	F?	1.50	116	− 8	2.1	1580	1560	− 220
RW Tauri	8.1	B5	1.76	135	−17	2.1	1580	1510	− 460
β Aurigae	2.8	A	2.08	136	+12	30.0	109	106	+ 23
R Canis Majoris	5.6	F	1.93	198	− 0	18.2	180	180	− 0
V Puppis	4.7	B1	2.77	230	−10	4.6	720	710	− 125
S Cancri	8.1	A	2.28	175	+34	2.4	1360	1130	+ 760
S Velorum	8.2	A	2.11	238	+ 5	2.5	1300	1300	+ 110
W Ursae Majoris	8.7	G	0.79	125	+47	20.0	164	112	+ 120
ST Carinae	9.5	A	1.44	252	− 3	2.0	1600	1600	− 80
Z Draconis	10.5	(A5)	1.67	96	+45	1.6	2050	1450	+1450
SV Centauri	9.1	A	2.74	263	+ 1	1.2	2600	2600	+ 50
W Crucis	9.0	Gp	100.0	265	+ 4	0.19	17200	17000	+1200
RZ Centauri	8.7	A	3.70	272	− 2	1.1	2900	2900	− 100
SZ Centauri	8.7	A	3.85	278	+ 3	1.1	2960	2960	+ 160
RR Centauri	8.0	F	1.30	282	+ 3	8.7	375	375	+ 20
U Ophiuchi	6.3	B8	1.78	351	+20	6.3	520	490	+ 180
u Herculis	5.0	B3	2.45	24	+32	5.2	620	530	+ 330
RS Sagittarii	6.3	A	3.28	326	−10	3.8	860	850	− 150
V Serpentis	10.1	A	2.63	343	− 1	0.8	3900	3900	− 70
RX Herculis	7.8	B9	1.57	10	+ 9	3.6	900	890	+ 140
RX Draconis	10.9	F	1.33	56	−22	2.3	1420	1310	− 530
U Sagittae	6.5	B8	2.77	21	+ 2	3.6	900	900	+ 30
SW Cygni	9.2	A	2.42	49	+ 7	1.4	2400	2380	+ 290
UW Cygni	10.7	A?	2.37	48	+ 3	0.7	4700	4700	+ 250
ZZ Cygni	10.7	A?	1.40	51	+ 4	1.2	2800	2800	+ 200
W Delphini	9.5	A	2.56	30	−15	1.1	2850	2750	− 740
WZ Cygni	10.1	A	1.58	48	− 4	1.4	2360	2350	− 160
U Pegasi	9.9	F?	1.07	74	−45	4.6	710	500	− 500
RT Sculptoris	9.7	F	1.48	40	−87	4.0	820	40	− 820
RS Cephei	10.4	Ap	2.24	100	+23	0.9	3800	3450	+1480
ϵ Aurigae	4.0	F8p	116.0	130	+ 2	1.1	3000	3000	+ 100
TT Aurigae	9.1	A	1.88	135	+ 1	1.8	1800	1800	+ 30
Z Orionis	9.7	A	3.90	162	− 5	0.7	4900	4900	− 430
RW Monocerotis	9.0	A	1.78	171	+ 1	2.0	1640	1640	+ 30
RR Velorum	10.3	A	1.32	243	+13	1.5	2200	2150	+ 500
SS Carinae	13.0	(A)	2.15	257	− 2	0.26	12400	12400	− 430
SU Centauri	8.8	F2	4.11	254	+12	2.8	1180	1160	+ 250
SS Centauri	8.7	B9	2.07	273	− 2	1.8	1800	1800	− 60
δ Librae	4.9	A	3.59	316	+41	6.6	490	370	+ 320
U Coronae	7.7	A	2.44	17	+57	2.8	1190	650	+ 990
Z Herculis	7.7	F	1.49	9	+17	8.8	375	360	+ 110
RR Draconis	10.1	A2	1.39	60	+24	1.8	1800	1650	+ 730
RZ Ophiuchi	10.4	G8	10.1	6	+ 3	1.1	2860	2850	+ 150

TABLE II—*Continued*

(1) Name	(2) *m*	(3) Sp.	(4) *A*	(5) λ	(6) β	(7) 1000 π	(8) *R*	(9) *R* cos β	(10) *R* sin β
β Lyrae	3.9	B8	6.0	30°	+14°	5.″2	620	600	+ 140
U Scuti	9.8	A	1.94	349	− 8	1.3	2500	2450	− 350
Z Vulpeculae	8.1	A	2.48	27	+ 4	2.2	1480	1480	+ 100
WW Cygni	10.1	Ap	2.66	45	+ 5	0.8	3900	3900	+ 350
VW Cygni	10.5	A	2.57	40	− 1	0.7	4700	4700	− 80
RW Capricorni	9.5	A	2.74	354	−28	1.1	3100	2750	−1460
UZ Cygni	10.5	A	4.42	61	− 9	0.42	7900	7800	−1250
RT Lacertae	9.6	G5	4.45	61	−10	3.1	1050	1040	− 180
Y Piscium	9.0	A	2.28	62	−50	1.6	2050	1320	−1570
SY Andromedae	10.9	A?	2.37	84	−18	0.6	5200	4950	−1600
TV Cassiopeiae	7.4	B9	2.13	86	− 3	3.3	990	990	− 50
Z Persei	9.7	A	1.47	112	−15	1.8	1800	1740	− 470
RY Persei	8.3	A2	3.41	110	−10	1.7	1980	1950	− 340
ST Persei	10.0	A	2.09	116	−16	1.1	3000	2900	− 830
RV Persei	10.9	A	2.95	131	−11	0.5	6300	6200	−1210
RW Geminorum	10.0	A	2.65	155	+ 2	0.9	3750	3750	+ 130
Y Camelopardalis	9.9	(A)	2.44	105	+30	1.0	3300	2850	+1650
RU Cancri	10.4	(F)	1.42	169	+35	2.6	1240	1010	+ 710
RW Ursae Majoris	10.8	G?	1.42	110	+61	4.2	780	380	+ 680
TW Draconis	7.6	B9	1.92	66	+45	3.3	980	690	+ 690
RV Lyrae	11.8	A	1.56	33	+ 8	0.6	5200	5150	+ 720
RS Vulpeculae	8.0	A	3.61	24	+ 4	1.6	2050	2050	+ 140
TT Lyrae	9.6	A	2.43	42	+11	1.1	2900	2850	+ 550
SY Cygni	11.0	G5?	1.75	36	+ 3	4.2	800	800	+ 40
RR Delphini	10.9	A	1.99	27	−19	0.8	4300	4050	−1400
VV Cygni	13.0	(A5)	1.72	55	− 2	0.5	6800	6800	− 240
TT Andromedae	11.5	A	1.84	74	−13	0.6	5200	5100	−1180
SX Cassiopeiae	9.1	G3	13.8	84	− 7	1.1	2850	2800	− 350
RX Cassiopeiae	9.3	K0	13.0	103	+ 9	1.6	2070	2050	+ 320
λ Tauri	3.9	B3	4.2	146	−28	5.2	620	550	− 290
RW Persei	9.6	A	2.27	126	− 4	1.2	2700	2700	− 190
RZ Aurigae	10.7	(A)	2.82	146	+ 3	0.6	5400	5400	+ 280
RR Puppis	9.9	A	2.01	223	− 7	1.2	2700	2700	− 330
X Carinae	8.6	A	2.45	242	−12	1.8	1800	1760	− 370
Y Leonis	9.5	A	1.47	171	+48	2.0	1650	1100	+1230
SW Centauri	9.2	A	1.67	265	+13	2.0	1650	1600	+ 370
SY Centauri	10.1	A	3.36	277	− 0	0.7	4950	4950	− 0
TX Herculis	8.7	A	1.07	34	+34	3.8	860	710	+ 480
SZ Herculis	9.8	(F)	1.23	25	+27	4.2	780	700	+ 370
RZ Scuti	7.6	B3	5.1	350	− 0	0.8	4100	4100	− 0
RZ Draconis	10.0	A	1.27	55	+26	1.8	1800	1620	+ 790
SX Sagittarii	9.3	A5	2.12	332	−14	2.4	1360	1310	− 330
RS Scuti	9.6	F	1.55	351	− 6	3.6	900	890	− 95
Y Cygni	7.6	A	1.83	45	− 7	3.8	860	850	− 105

shortest radius in the equatorial plane has been taken. In one or two indeterminate cases, the mean of the limiting possible values has been used in the calculations. This quantity A is the radius of the brighter component (taking the sun's radius as unity), divided by the cube root of the ratio of the mass of the system to twice the sun's mass. From the data of Table I it appears that a good approximation to the true radius may be obtained by increasing the tabular value by two-thirds of itself for spectrum Bo, one-half for B5, one-third for A, and one-sixth for F. Columns (5) and (6) give the galactic longitudes and latitudes of the stars (taken in all but a few instances from the list in *Harvard Annals*, **56**, 187–191). The assumed position of the galactic pole is 12^h40^m, $+28°$. Column (7) gives the parallax computed by equations (1) and (4). To avoid the printing of needless ciphers, the values of $1000\,\pi$ are tabulated. Column (8) gives the corresponding distance R in light-years, and columns (9) and (10) the components of this distance, resolved parallel and perpendicular to the galactic plane passing through the sun.

The stars are arranged in four groups, according to the accuracy of their orbital elements, those in each group being in order of right-ascension.

In estimating the spectra of the seven stars which were too faint to be classified on the Harvard plates recourse was had to the fact that there is a marked correlation between the spectral type and the density (and hence the values of A). When A exceeded 2.0 the spectrum was assumed to be of Class A; when it was between 2.0 and 1.6, of Class A5; and when it was between 1.6 and 1.2, of Class Fo. It should be borne in mind that the correlation here utilized, though fairly definite, is far from absolute, so that these estimates, and the numbers derived from them, are subject to considerable uncertainty.

The most conspicuous characteristic of the parallaxes estimated as in Table II is their extreme minuteness. The mean parallax of all the 90 stars comes out only $0''.0033$. Only four of them (β Aurigae, β Persei, W Ursae Majoris, and R Canis Majoris) have estimated parallaxes exceeding $0''.01$. The mean for the remaining 86 stars is $0''.0023$; 48 of these have estimated parallaxes

less than 0".002, and 19 of these are below 0".001. These small parallaxes are, however, confirmed by direct observation in the few cases in which observations have been made. The observed values, corrected for the probable parallax of the comparison stars, are given in Table III, with weights, assigned by the writer on the basis both of the probable errors found by the observers and of the general reliability of the methods of observation. The probable errors of the weighted means are derived from the residuals for the individual determinations in the ordinary way. The values estimated in the present paper are repeated for comparison.

TABLE III

Star	Observer	Parallax	Probable Error	Weight
β Persei	Chase	0".044	±0".025	2
	Russell	0.011	±0.025	2
	Flint	0.130	±0.026	1
Mean observed parallax		0.048	±0.019	
Estimated parallax		0.026		
β Aurigae	Flint (1st series)	0.000	±0.031	2
	Tikhoff	0.023	±0.019	4
	Flint (2d series)	0.034	±0.020	4
	Iewdokimow	0.150	±0.042	1
Mean observed parallax		0.034	±0.015	
Parallax if a member of the Ursa Major group		0.019		
Estimated parallax		0.030		
Y Cygni	Slocum	0.005	±0.010	
Estimated parallax		0.004		

It would seem that direct observations for parallax are worth while, at present, only in the case of the four nearest systems, already mentioned; and even in these cases only the most precise methods, especially as regards freedom from systematic error, can be of any value.

The extremely small parallaxes derived for the general run of these variables may seem surprising, because they are less than the probable mean parallaxes of all the stars of similar magnitude. But evidence is gradually accumulating that the stars of the ninth magnitude and fainter are for the most part of the "later" spectral

classes, and, since the eclipsing variables are mainly of Class A, there is no reason to suppose them typical of the whole. They may very well be (as is assumed here) stars of greater actual luminosity, and hence remoter than the general run of those of similar visual magnitude.

It should, however, be expressly borne in mind that all the computations so far made depend upon the assumption that there is no loss of light by absorption in passing through interstellar space, even for thousands of years. If absorption of any kind exists, the estimated distances will be too great.

Except for the very remotest stars, the correction to the estimated parallaxes for absorption of light in space takes a remarkably simple form. Suppose that there exists a uniform absorption, amounting to d magnitudes for each distance of 32.6 light-years (corresponding to a parallax of $0''.10$). In the absence of absorption, the relation between the absolute and apparent magnitudes of any star would be

$$m = M - 5 - 5 \log \pi$$

but in the presence of absorption it will be

$$m = M - 5 - 5 \log \pi + \frac{d}{10\pi} \qquad (5)$$

If now π' is the parallax estimated from the difference of the absolute and observed magnitudes, on the hypothesis that there is no absorption, we shall have

$$5 \log \pi' = 5 \log \pi - \frac{d}{10\pi}$$

whence

$$\pi' = \pi \cdot 10^{\frac{-d}{5\pi}} = \pi \cdot e^{-0.0461\frac{d}{\pi}} = \pi - 0.0461\, d + 0.00106\frac{d^2}{\pi} + \ldots . \qquad (6)$$

Hence, except for very small values of π, the correction for absorption can be very approximately made, by adding to the parallaxes computed on the assumption that space is transparent the quantity $0''.0461\, d$. For example, King[1] has recently concluded from a study of the color-indices of stars of known parallax that the value

[1] *Harvard Annals*, **76**, 10, 1914.

of d (corresponding as above to a distance of 32.6 light-years) is 0.019 mag. for the visual rays, and 0.038 mag. for the photographic rays. If these values are accepted, the correction to be added to the larger parallaxes determined from observed visual magnitudes is $0''.0461 \times 0''.019$ or $0''.00088$, while for parallaxes determined from photographic magnitudes, it is $0''.0018$. For remote stars the correction is smaller, as is illustrated by Table IV, which is based upon the value $d = 0.019$. It appears, therefore, that, with this value of d, the mere addition of $0''.0008$ to all the estimated parallaxes will accomplish the correction for absorption within $0''.0001$, except for a few of the remotest stars.

TABLE IV

$1000\,\pi$	$5 \log \pi$	$\frac{d}{10\,\pi}$	$5 \log \pi'$	$1000\,\pi'$	$1000\,(\pi - \pi')$
$10''.0$	−10.00	0.19	−10.19	$9''.16$	$+0''.84$
5.0	11.50	0.38	11.88	4.21	0.79
2.5	13.01	0.76	13.77	1.76	0.74
1.5	14.12	1.27	15.39	0.84	0.66
1.0	15.00	1.90	16.90	0.42	0.58
0.5	16.50	3.80	20.30	0.09	0.41

Other investigators, working upon the same assumption of a space-absorption varying inversely as the fourth power of the wave-length, have found smaller values of the coefficient d; for example, Kapteyn, for the visual rays, derives $d = 0.0030$.[1] It is, however, not improbable that at least a part of any existing absorption arises from the presence in space of sensible particles of matter, whose influence is the same for all wave-lengths, and that the values of the absorption coefficient derived from the color-indices, on the assumption just mentioned are too small. King's value, 0.019, for d will therefore be employed in the present discussion as indicating the order of magnitude of the effect to be expected, if it really exists.

It appears then, that the introduction of corrections for such absorption would probably increase the mean parallax of the eclipsing variables here studied to little, if at all, above $0''.004$, or

[1] *Astrophysical Journal*, **30**, 399, 1909.

0".003, if the four nearest stars are rejected. The very great distances, exceeding 5000 light-years, which are computed above for certain stars, would, however, be greatly diminished. With $d = 0.019$, the parallaxes and distances of the three remotest stars become: W Crucis, 0".00068, 4900 light-years; SS Carinae, 0".00078, 4200 light-years; UZ Cygni, 0".00102, 3200 light-years. It is noteworthy, too, that the estimates for the first two of these stars are based on photographic magnitudes. If King's value of d for the photographic rays, 0.038, is adopted for these stars, their estimated distances are reduced to 3100 and 2800 light-years; but, for reasons already stated, this may be going too far.

We may now consider the distribution of these eclipsing systems in space. Of the 90 stars, 64 lie between 0° and 180° of galactic longitude, and only 26 in the opposite hemisphere. This is obviously a result of the much more thorough study which has been given to the light-curves of northern stars, and has no cosmical meaning.

The distribution in galactic latitude is, however, significant. It is well known that the eclipsing variables are strongly concentrated toward the Milky Way. For the stars here investigated the distribution is as follows:

	Galactic Latitude					
	+90° to +30°	+30° to +10°	+10° to 0°	0° to −10°	−10° to −30°	−30° to −90°
Number.....	12	13	23	21	18	3

The deficiency near the southern galactic pole is doubtless due to the paucity of observations in this region, which would also explain the slight preponderance of northern latitudes (48 as against 42), but, even if allowance is made for this, the density of distribution in the heavens is some six times as great within 10° of the Galaxy as in the rest of the sky. When we pass from these apparent positions to the real co-ordinates in space, it appears at once that these stars are strongly concentrated near the galactic plane.

With the co-ordinates computed on the assumption that space is transparent, we find that 63 of the 90 stars are within 500 light-

years of the plane passing through the sun parallel to the galactic equator. Only 12 stars are more than 1000 light-years from this plane, and but three more than 1500 from it, the extreme distances being −1600 and +1650. Of the distances projected upon the galactic plane, however, 28 are less than 1000 light-years, 23 between 1000 and 2000, and 24 between 2000 and 4000, leaving 15 exceeding 4000 light-years.

This is in agreement with the accepted opinion that the region within which the stars are at all densely distributed extends much farther in the direction of the galactic plane than at right angles to it. The sun appears to be not far from the central plane of densest distribution. The mean value, with regard to sign, of $R \sin \beta$ is +10 light-years; but we have seen above that the observational preference for northern stars has discriminated against those in high negative galactic latitudes, there being only 3 between −30° and −90° against 12 between +30° and +90°. The average distance of these 15 stars from the galactic plane is 820 light-years. If we assume that 9 similar southern stars have so far escaped the detailed observation necessary for the calculation of their orbits, but would be included if the whole heavens had been impartially studied, their inclusion would make the general mean for $R \sin \beta$ −65 light-years. It seems therefore probable that the sun is slightly, but sensibly, to the north of the median plane of the system of stars.

The average distance, regardless of sign, of the stars from the plane passing through the sun, is 436 light-years (which would be raised to 470 by the inclusion of additional southern stars as assumed above). The computed average distance from the galactic plane appears, however, to be to some degree a function of the distance projected on this plane, as is shown by Table V (in which

TABLE V

	Limits of $R \cos \beta$				
	0 to 1000	1000 to 2000	2000 to 4000	Over 4000	All Together
Number of stars	28	23	24	15	90
Mean of $R \cos \beta$	550	1470	2820	6550	2400
Mean of $R \sin \beta$ regardless of sign	256	485	444	685	436

all distances are given in light-years). The inclusion of more stars near the southern galactic pole (for most of which $R \cos \beta$ is relatively small) would raise the first of the quantities in the last line to about 370 light-years; but a decided progression would still exist. It does not appear very probable that the thickness of the region within which the stars lie actually increases with increasing distance from the sun; the alternative suggests itself that the distances of the remoter stars have been overestimated, as would be the case if their light suffered absorption in reaching us.

It seemed, therefore, desirable to recompute their positions, assuming a coefficient of absorption of 0.019 as discussed above. The resulting distribution may be summarized as in Table VI. The tendency toward increase of the computed thickness of the

TABLE VI

	Limits of $R \cos \beta$						
	0 to 500	500 to 1000	1000 to 1500	1500 to 2000	2000 to 2500	Over 2500	All Together
Number of stars	14	23	17	18	9	9	90
Mean $R \cos \beta$	300	740	1230	1730	2280	3150	1350
Mean $R \sin \beta$ regardless of sign	218	318	270	298	246	302	280

starry region with increasing distance has now disappeared; but it would be premature to regard this as evidence of the reality of the absorption of light in space.

However this may be, it is evident that the extension of the region occupied by these stars is several times greater in all directions along the galactic plane than it is at right angles to it. In the latter direction, the limit of the region in which the stars are at all thickly sown is reached far within the distance at which they would become invisible in small telescopes; while along the galactic plane there is no evidence that our present studies have penetrated to the limit.

All these conclusions are in excellent agreement with those recently derived by Hertzsprung from a study of the short-period variables, on principles very similar to those of the present dis-

cussion.[1] He finds, from the parallactic motions of 13 of these Cepheid variables, which appear in Boss's *Preliminary General Catalogue*, that their mean absolute magnitude, on Kapteyn's scale, is -2.3 ± 0.5. Combining this with Miss Leavitt's discovery that among the variables in the Small Magellanic Cloud (whose periods and light-curves resemble those of the stars under consideration) the logarithm of the period increases with the mean brightness at the rate of 0.48 for each magnitude, and assuming the same law to hold for the isolated variables of short period, he deduces an expression for the mean absolute magnitude of such a variable which, on Kapteyn's scale, becomes

$$M = -2.3 - 2.1 \log \frac{P}{6.6}$$

when P is the period in days. Parallaxes and distances may then be computed for all the variables of this class whose periods and range of magnitude are known.

As no detailed list of parallaxes, etc., is given in Hertzsprung's paper, the writer has recomputed the parallaxes and co-ordinates in space for the 67 available stars found in the list in the *Harvard Annals*, **56,** 191 ff. (excluding as Hertzsprung does those with periods less than one day, which appear to form a class by themselves). This material is identical with Hertzsprung's (except that SZ Centauri has been excluded, since it is now known to be an eclipsing variable), and the only addition to his results has been the computation of distances, co-ordinates, etc., on the assumption that space-absorption exists, with the coefficient $d = 0.019$ (as above). The results of this discussion are strikingly similar to those derived above for the eclipsing variables. The short-period variables appear to be, on the average, about half as far away again, their computed mean distances being 4100 light-years if space is transparent, and 2040 with the assumed coefficient of absorption, as against 2400 or 1350 light-years for the eclipsing variables. This difference arises from the differences in the real luminosity of the two sets of stars, only 8 of the 90 eclipsing variables having estimated absolute magnitudes as bright as the faintest of the others.

[1] *Astronomische Nachrichten*, **196**, 205, 1913.

Since the search for variable stars has been carried down to about the same apparent magnitude in both cases, the difference in the mean distance is natural.

The short-period variables, however, are much more closely concentrated about the galactic plane than the others, their average distances from it being 260 light-years if there is no absorption, and 172 with the assumed absorption, while the corresponding values for the eclipsing variables are 436 and 280 light-years.

TABLE VII

A. Space Assumed Transparent

	Limits of $R \cos \beta$				
	0 to 2000	2000 to 3000	3000 to 6000	Over 6000	All Together
Number of stars	17	16	15	19	67
Mean $R \cos \beta$	1080	2500	4100	8100	4100
Mean $R \sin \beta$ regardless of sign*	158	214	285	368	260

B. Absorption with $d = 1.019$

	Limits of $R \cos \beta$					
	0 to 1000	1000 to 1500	1500 to 2000	2000 to 3000	Over 3000	All Together
Number of stars	11	8	19	14	15	67
Mean $R \cos \beta$	670	1220	1720	2440	3400	2040
Mean $R \sin \beta$ regardless of sign*	151	131	127	151	162	172

* These distances are measured from a plane passing 100 light-years south of the sun.

The median planes of the two sets of stars are apparently nearly coincident, if allowance is made for the effect of observational preference for northern eclipsing variables.[1] If space is transparent, the median plane for the eclipsing variables appears to be 65 light-years south of the sun, and that for the short-period variables 125 light-years south of the sun. The introduction of absorption reduces these distances to 40 and 75 light-years, respectively.

[1] No such allowance need be made for the stars of short period because the observational material required to furnish the data needed in the computations is very much less, and the necessary information is available for all parts of the heavens.

The same curious increase in the computed mean distance from the galactic plane with increasing distance from the sun is seen in Hertzsprung's figures, and the introduction of the hypothesis of absorption again removes it, as is shown by Table VII, A and B, similar to those already given.

The reappearance of this phenomenon with these quite independent data lends some support to the idea that it is really evidence of the absorption of light in space.

It may be desirable to add a table (VIII) showing in somewhat greater detail the distribution of the distances of the stars from the galactic plane.

TABLE VIII

	Distance from Galactic Plane in Light-Years											
	Over −1200	−1200 to −800	−800 to −600	−600 to −400	−400 to −200	−200 to 0	0 to +200	+200 to +400	+400 to +600	+600 to +800	+800 to +1200	Over 200 +1
A. No absorption												
Eclipsing variables . .	6	3	1	6	9	17	20	12	3	7	1	5
Short-period variables	....	1	1	6	13	13	17	11	2	3	....	....
B. $d=0.019$												
Eclipsing variables . .	....	3	2	7	10	20	26	10	7	0	5	....
Short-period variables	....	....	....	1	7	23	24	12	....	....	....	....

The results of the independent, though similar, investigations of Hertzsprung and of the writers may be summarized as follows:

A considerable majority of the eclipsing variables, and almost all those of short period, lie within a region bounded by two planes 1000 light-years apart, and parallel to the galactic equator, whose median plane passes about 100 light-years south of the sun. Almost all the rest of these stars lie within 500 light-years on each side of this region. Within this region, the stars extend in all directions to the limit of the present investigations. This limit, if space is transparent, must be at least 8000 light-years. The assumption of a plausible amount of absorption of light in space cuts this down to about 4000 light-years, and removes the anomaly of the apparent widening-out of the starry region with increasing distance from the sun.

Our "universe" of stars must be at least some thousands of light-years in diameter. The best available method of finding its limits (if these are not set by the absorption of light) is by the investigation of very faint variable stars of the Cepheid type. The rarity of variables among the fainter stars in the Milky Way[1] suggests that a limit exists, and is accessible to present means of investigation. It is of interest in this connection that Hertzsprung (assuming space transparent) has found a distance of 30,000 light-years for the Small Magellanic Cloud.[2] If at this distance, it must be about 1000 light-years in diameter, and a small affair compared with the star cloud of which the sun is one of the fainter members.

PRINCETON UNIVERSITY OBSERVATORY
August 15, 1914

[1] D'Esterre, *M.N.*, **74**, 308, 537, 1914.

[2] *Loc. cit.* Misprinted as 3000.

AVOGADRO'S CONSTANT AND ATMOSPHERIC TRANSPARENCY[1]

By F. E. FOWLE

In an earlier number of the *Astrophysical Journal*[2] were derived values for the vertical transmissibility ($a_{a\lambda}$) of radiation through dry air above Mount Wilson together with certain correction factors ($a^{w}_{w\lambda}$) by which these could be altered for moist air containing w cm of precipitable water in the form of vapor. By means of Rayleigh's formula connecting the scattering of light passing through a gas with the number of molecules present, these dry-air coefficients were used to compute the number of molecules n_0 per cubic centimeter of a gas at 76 cm pressure and 0° Centigrade. This formula of Rayleigh's has been shown to be consistent with very different light-theories.[3] From n_0, N, Avogadro's constant, or the number of molecules per gram-molecule, directly follows. A gram-molecule is the amount of a substance equal to m grams where m is the molecular weight of the substance. The approximate agreement of these rather rough determinations of n_0 with the best value of this constant from other methods was used as an argument for the correctness of our determinations of the atmospheric losses in solar-constant computations.

It is perhaps worth while to redetermine with greater refinements the value of Avogadro's constant derived by this method. Mr. L. V. King,[4] regarding the process based upon molecular scat-

[1] Published by permission of the Secretary of the Smithsonian Institution.

[2] *Astrophysical Journal*, **38**, 392, 1913.

[3] Rayleigh, *Encyclopaedia Britannica*, 11th ed., XXV, 202 ("Sky"), 1911; Natanson, *Bull. intern. de l'Académie des sciences de Cracovie*, January 5, 1914.

[4] *Philosophical Transactions of the Royal Society of London*, **212** A, 375, 1913. *Nature*, **93**, 557, 1914. It is somewhat incorrect to state that our transmissibility coefficients rest "ultimately on the ratio of two galvanometer deflections . . . . quantities measurable to well within 1 per cent" (*loc. cit.*). Their accuracy depends rather on the constancy of the sky during about 2 hours for which our 6 observations furnish some indication. In those parts of the spectrum little affected by water vapor an accuracy considerably better than 1 per cent is generally obtainable.

tering as of considerable value as an independent method of determining this constant, has used our observed moist-air coefficients for this purpose but has proceeded along quite a different path to his end. It is proposed to offer a comparison of our procedures.

OBSERVATIONS

Briefly, the following is the method of deriving the dry-air transmission coefficients which will be used in my procedure. They were obtained for Mount Wilson at 30 different wave-lengths between 0.34 μ and 2.24 μ. The logarithms of the observed transmission coefficients were plotted as ordinates against the corresponding quantities of precipitable atmospheric moisture as abscissae, and the best representative curves (which appeared to be right lines) were produced by a short extrapolation to zero of moisture. From the consideration of the slope of these right lines, factors expressing the effect of water vapor on the atmospheric transmission were determined for the 30 wave-lengths. The process and results are given in more detail in the paper cited.

In Table I are given the data thus obtained. In columns two and three will be found the zenith transmission coefficients for radiation through dry air above Mount Wilson ($a_{d\lambda}$), altitude 1730 m, barometer 62.3 cm, for 1910–1911 and 1913 respectively. During 1912 the variability from day to day in the amount of dust suspended in the atmosphere subsequent to the eruption of Mount Katmai[1] rendered the values then obtained useless for the present discussion. The column headed Δ contains the fractional deviations of the 1913 observations from the earlier mean and probably indicates the presence of a remnant of the suspended dust from the Katmai eruption causing still a loss of from 2 to 3 per cent; for, assuming $a_{d\lambda}$ the coefficient of transmission for this dust at the wave-length λ during 1913, then the fractional deviations are

$$\frac{a_{1910-1911}-a_{1913}}{a_{1910-1911}}=\frac{a_{d\lambda}-a_{d\lambda}a_{d\lambda}}{a_{d\lambda}}=1-a_{d\lambda}$$

or the amount of radiation lost because of the dust.

[1] *Annals of the Astrophysical Observatory of the Smithsonian Institution*, **3**, 211, 1913; *Smithsonian Miscellaneous Collections*, **60**, 1, 1913.

The observations of 1913 were excellent in quality throughout the spectrum, whereas those of 1910–1911 both in the infra-red and in the ultra-violet were less satisfactory. Accordingly for the first three ultra-violet places in the 1910–1911 column where field-light doubtless made the values of my earlier communication too

TABLE I

ATMOSPHERIC TRANSPARENCY AND n_0

WAVE-LENGTH Å	TRANSMISSION COEFFICIENTS						k	REFRACTION COEF. 1.000	n_0
	DRY AIR. $a_{g\lambda}$			WATER VAPOR, $a_{w\lambda}$					
	1910–1911	1913	Δ	1910–1911	1913	Mean			
0$^{\mu}$.3504	(0.632)	0.614	(0.028)	0.917	0.933	0.925	0.459	3010	.....
.3600	(.655)	.637	(.028)	.940	.948	.944	.423	3002	275×10^{17}
.3709	(.686)	.667	(.028)	.959	.923	.941	.377	2994	273
.3838	.713	.689	.033	.959	.929	.944	.338	2986	264
.3974	.752	.738	.019	.962	.962	.962	.285	2978	271
.4127	.783	.763	.026	.965	.938	.952	.245	2970	269
.4307	.808	.792	.020	.968	.944	.956	.213	2962	259
.4516	.840	.816	.029	.967	.955	.961	.174	2954	262
.4753	.863	.836	.031	.973	.951	.962	.147	2947	.....
.5026	.885	.859	.029	.976	.957	.966	.122	2939	Mean=
.5348	.898	.873	.028	.980	.964	.972	.108	2931	268×10^{17}
.5742	.905	.877	.031	.974	.966	.970	.100	2924	.....
.5980	.913	.885	.031	.978	.973	.975	.091	2921	.....
.6238	.929	.897	.034	.977	.973	.975	.074	2918	.....
.6530	.938	.916	.023	.987	.975	.981	.064	2915	.....
.6858	.959	.935	.025	.985	.977	.981	.0419	2911	.....
.7222	.970	.947	.024	.989	.977	.983	.0304	2907	.....
.7644	.979	.956	.024	.985	.977	.981	.0212	2904	.....
.8130	.980	.958	.022	.990	.981	.985	.0202	(2901)	.....
.8634	.982	.965	.017	.989	.983	.986	.0182	.....	.....
0.9861	.987	.974	.012	.991	.989	.990	.0131	.....	.....
1.1474	.987	.973	.014	.988	.988	.988	.0131	.....	.....
1.3019	.986	.980	.006	.990	.984	.987	.0141	.....	.....
1.4520	.989	.984	.005	.988	.988	.988	.0111	.....	.....
1.6032	0.983	.989	−0.004	0.986	.984	.985	0.0171	.....	.....
1.738	.....	.985	.....	.....	.989	.989	.....	.....	.....
1.870	.....	.984	.....	.....	.987	.987	.....	.....	.....
2.000	.....	0.983	.....	.....	0.986	0.986	.....	.....	.....

high, new values have been computed from the excellent coefficients of the 1913 column assuming $\Delta=0.028$. Because of the less satisfactory character of the infra-red values especially for the observations of 1910–1911, the falling-off of the fractional deviations in the infra-red may not be real. The average of the 16

better values of column 4 gives 0.027 as the scattering due to the dust in the air above Mount Wilson during 1913.

The next three columns give the correcting factors ($a_{w\lambda}$) for 1 cm precipitable water in the form of atmospheric vapor for 1910–1911, 1913, and the mean, respectively. When the altitude of a station is such that dust is practically absent, say above 1000 meters, the transmissibility of radiation from a celestial body at a zenith distance z through the atmosphere when it contains w cm of precipitable water vapor and the barometer reads p cm, is[1]

$$\{(a_{a\lambda})^{p/76}(a_{w\lambda})^{w}\}^{\sec z}$$

No account is taken by this formula of selective absorption.

Then follows a column containing values of the "coefficient of attenuation" k which are related to a by the equation $\log_e a_{a\lambda} = k$. The coefficients of refraction are from values determined for dry air by Kayser and Runge.[2]

AVOGADRO'S NUMBER

The determination of Avogadro's number from the observed scattering of radiation in passing through a gas is based upon Rayleigh's formula. If n_0 is the number of molecules in a cubic centimeter of a gas at 0° C. and 76 cm pressure, k as defined in the last paragraph, n the index of refraction, λ the wave-length in centimeters of the radiation, p the atmospheric pressure in centimeters and equal to 62.3 at Mount Wilson, H the height in centimeters of a homogeneous atmosphere at 0° C. producing a pressure at its base of 76 cm and equal to 7.99×10^5, then Rayleigh's formula may take the form:

$$k = \frac{32\pi^3(n-1)^2 Hp}{3n_0\lambda^4 76}.$$

N, Avogadro's number, $= n_0 \times 32$ (molecular weight oxygen) $\times 699.7$ (cubic centimeters of oxygen 0° C., 76 cm pressure, weight 1 gram) $= 22390n_0$. If dust is present in appreciable amount in the atmos-

[1] See *Meteorologische Zeitschrift*, **31**, 270, 1914; *Monthly Weather Review*, **42**, 2, 1914. Comparisons are given in these communications of computations by this formula with actually observed transmissions for altitudes of 50, 90, 100, 1160, 1730, 1950, 3260, and 4420 meters.

[2] *Abhandlungen Akademie der Wissenschaften in Berlin*, 1893.

phere then $(k-d)$ must be equated to the above expression, k being the coefficient of attenuation belonging to the dust.

In the upper curve of Fig. 1 are plotted the values of $a_{a\lambda}$ (column 2 of the table) as ordinates against the corresponding wave-lengths as abscissas. In the lower curve the values of k (column 8) are

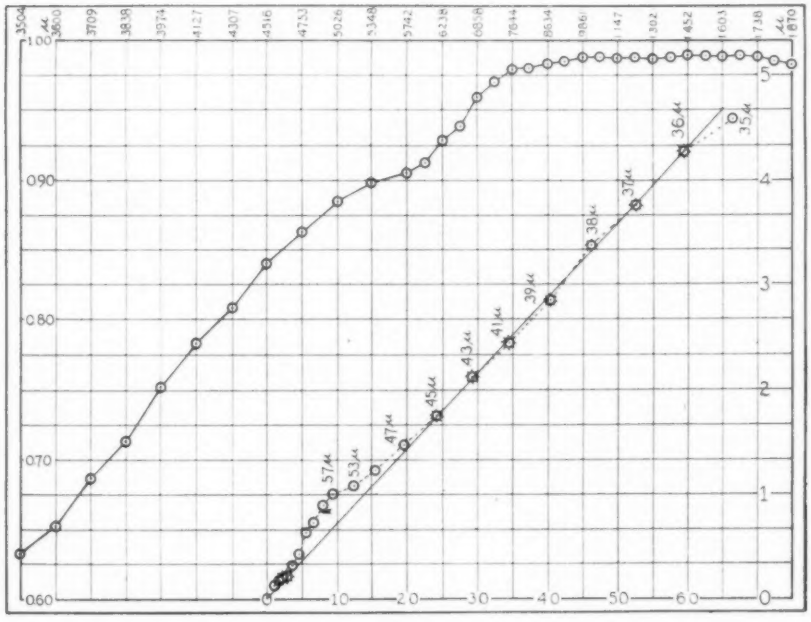

FIG. 1

Upper curve: ordinates, transmissibility of radiation through dry air vertically above Mount Wilson, 1910–1911, $(a_{a\lambda})$; abscissae, wave-lengths in μ

Lower curve: ordinates, values of k, where $\log_e a_{a\lambda} = k$; abscissae, $\lambda^{-4} \times 10^{-16}$

used as ordinates against those of λ^{-4} as abscissas. In the equation for k, were d zero and n constant, then the points of the latter plot should lie on a right line passing through the zero of co-ordinates. Mr. King makes plots similar to this last one except that the *observed* k's for *moist* air are used. Subsequently our procedures and interpretations diverge. He assumes that d is not zero and passes the best right line through the points from the ultra-violet up to about $0.610\,\mu$. Then he proceeds to draw a

steeper right line through the remaining points of longer wave-lengths. It is difficult to see the physical significance of this latter step or why the scattering due to the dust should suddenly and rapidly decrease in this part of the spectrum. Indeed he states "the precise cause of this well marked discontinuity furnishes a point which must be left for further investigation." The slant of the line for the violet end taken with a mean value of the index of refraction gives his value for n_0.

To me it seems the data admit of a very different interpretation. In my view the run of the dry-air coefficients is consistent with a practically dust-free air above Mount Wilson and the departures of the points between wave-lengths 0.47 μ and 0.76 μ from the representative right line are due to the selective absorption of the gases of our atmosphere. In this region Rowland gives some 440 atmospheric lines exclusive of those due to water vapor. When this region is passed the points naturally approach the right line again. Rayleigh's formula does not hold for selective absorption and therefore the points in this region should be omitted from the discussion.

Returning now to the table, in the last column are given the values of n_0 as computed separately for the upper 7 starred points in the lower plot. Their mean gives

$$n_0 = 2.68 \times 10^{19}, \qquad N = 6.00 \times 10^{23}$$

The values of the infra-red points where they next approach the representative right line have not so much weight, for here a change of 1 per cent in the observed values of the atmospheric transmission changes k, and therefore n_0 and N, by 100 per cent. The effect of a very small loss due to dust would therefore greatly influence values determined from the infra-red observations alone, whereas it would have comparatively little effect on the violet values. Attention has already been called to the fact that these infra-red points were not very satisfactorily determined during 1910–1911. However, using the red-end values of the greatest wave-lengths for which the indices of refraction are known, 0.76 μ and 0.81 μ, together with the seven values just used and the more complete equation containing d, a least-squares reduction gives

$$n_0 = (2.73 \pm 0.02) \times 10^{19}, \quad N = (6.11 \pm 0.05) \times 10^{23} \quad d = 0.005 \pm 0.002$$

The value of a corresponding to $d=0.005$ is 0.995, showing a very small loss due to dust during the years 1910–1911 as already inferred.

Since the first three values of the 1910–1911 column built up from the 1913 data may be open to some criticism, a least-squares reduction using the same wave-lengths and the more complete equation has been made for the 1911 data. The following values resulted:

$$n_0=(2.69\pm0.03)\times10^{19}, \quad N=(6.02\pm0.06)\times10^{23}, \quad d=0.026\pm0.003$$

The value of a corresponding to $d=0.026$ is 0.974 or a loss due to the dust in the air for 1911 of 0.026 corresponding very closely with the mean obtained from column 4 or 0.028.

SUMMARY

In the foregoing communication are given coefficients for the transmissibility of radiation of various wave-lengths through the dry air vertically above Mount Wilson together with factors and formula for computing the transmissibility for moist air for other zenith distances and altitudes where dust has become a negligible quantity (above 1000 meters). No account, however, is taken in the formula of selective absorption.

By means of Rayleigh's formula connecting the scattering of light passing through a gas with the number of molecules, these coefficients have been used to compute the number of molecules n_0 in a cubic centimeter of a gas at 76 cm pressure and 0° C. The merits of the present reductions over those of my earlier paper lie in using the index of refraction proper to each point in place of a mean value, in better values for k, and in a more accurate value of p, the value before used being taken at an appreciably higher altitude on the mountain than our observatory. The mean results give

$$n_0=(2.70\pm0.02)\times10^{19}$$

Avogadro's number, or the number of molecules per gram-molecule, corresponding to this value is

$$N=(6.05\pm0.04)\times10^{23}$$

The agreement of the above value for n_0, 2.70×10^{19}, with what is perhaps the best value from other methods, $2.705 \pm 0.005 \times 10^{19}$ (Millikan), must give weight to the accuracy of the estimation of the atmospheric losses in the determinations of the solar radiation by the Smithsonian Observatory.

A remnant of the volcanic dust from the eruption of Mount Katmai, Alaska, in 1912, scattering somewhat less than 3 per cent of the incident solar radiation, is indicated by the 1913 transmission coefficients. It is perhaps worth noting that, fine as this dust must be to have remained suspended in the upper air over a year, its scattering of radiation scarcely varies with the wave-length, at least between the limits $0.38\ \mu$ and $0.81\ \mu$.

Astrophysical Observatory
Smithsonian Institution
Washington, D.C.
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NEW VARIABLES IN THE CENTER OF MESSIER 3[1]

By HARLOW SHAPLEY

In the investigations of the variable stars in the globular cluster Messier 3 by Professor Bailey at Harvard,[2] the central portion could not be studied successfully on his plates because the great density of stars made it impossible to distinguish individual images. Thus practically all of the region within one minute of arc of the center of the cluster has remained unexplored. Outside the central burned-out nucleus Bailey found 137 variables,[3] and for 110 of them has determined the periods and light-curves, finding that in all cases the periods are shorter than eighteen hours and that the variation is of the typical cluster type. Judging from the relation between the number of variables and the total number of stars at different distances from the center, Bailey estimated that there should be about twelve more variables in the central part of the cluster.

Photographs of the cluster made with the 80-foot-focus Cassegrain combination of the 60-inch reflector have a scale sufficiently large to permit a relatively easy examination of the individual brighter stars of the central region. Six plates have been obtained on three different nights, three with exposures of an hour each and three with exposures of fifteen minutes. The intercomparison of the plates in the Zeiss stereocomparator resulted in the discovery of more than 30 new variable stars. For several of these it is not possible to be absolutely certain of the variation, because either the ranges are small or the variation is observed on only two of the plates available. For 23 of the stars, however, there can be no doubt of the variability. It may be possible later to add a few more to this list of variables from among those suspected. Only two of the 23 are more than one minute of arc from the center of the cluster. The outer portions of the cluster were not systematically

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 91.

[2] *Harvard Annals*, **38**; *ibid.*, **78**, Part I.

[3] The later measurements of the plates at Harvard indicate that about five stars of the original list are probably not variable and that a few others are somewhat doubtful.

examined, for Bailey's thorough study no doubt makes that unnecessary.

In Table I the new variables are listed in order of right ascension. All but two of them are contained in von Zeipel's catalogue of Messier 3, which gives the positions of 1571 stars.[1] The numbers in the second column of Table I, and the right ascensions and declinations in the third and fourth columns are taken from that work. For No. 1 and No. 14 the positions were determined by reference to neighboring stars. In a large number of cases the catalogue position refers to the mean place of a double, triple, or multiple star which could not be resolved on the plates measured by von Zeipel and usually was not even suspected of being other than a single star. In such instances the notes following the table indicate which component is the variable.

The last two columns of Table I give, respectively, the maximum and minimum magnitudes observed on my plates. These numbers should not be taken as in any way indicating the total range. For many of the variables the length of the exposure no doubt minimizes the brightness at the sharp-pointed maxima; and many of them may be very close composite stars with one component varying through a large range, but without having conspicuous effect on the image of the composite mass. The magnitudes are based on estimates referred to Bailey's series of comparison stars as standards.

NOTES ON THE INDIVIDUAL STARS IN TABLE I

No. 1.—The new variable is the preceding companion of von Zeipel's No. 486, which is also Bailey's variable No. 29. Bailey partially resolved the double and considered at least one of the pair variable. Both components vary through a wide range.

No. 3.—Von Zeipel thought this was perhaps a double and made measures on the two ends of a nebulous streak as well as upon the middle. The star appears single on the Mount Wilson plates. (No star is seen in the neighboring catalogued position of No. 655.)

No. 4.—This is apparently a composite star, but it is the central nucleus that undergoes variation.

[1] *Annales de l'Observatoire de Paris*, **25**, F1–F101, 1908.

No. 5.—Von Zeipel's No. 676 is composed of five distinct stars, of which the variable is the brightest and most centrally located.

No. 7.—The variable is the brighter and southern component of a close double.

No. 9.—Von Zeipel's position refers to the center of mass of the image of a double. The variable precedes its faint companion and at minimum is equal to it in brightness.

TABLE I

NEW VARIABLE STARS IN MESSIER 3

No.	VON ZEIPEL'S NUMBER	α 1900	δ 1900	MAGNITUDE	
				Maximum	Minimum
		13^h37^m	28°		
1.....	.....	30.12	51′46″.5	15.4	16.9
2.....	620	32.785	52 1.31	15.6	17.0
3.....	638	33.005	53 16.59	16.0	16.8
4.....	654	33.151	52 39.27	16.2	16.7
5.....	676	33.440	52 31.47	15.2	16.8
6.....	678	33.479	52 18.38	15.5	16.8
7.....	698	33.810	53 36.42	15.3	16.7
8.....	703	33.870	52 19.52	16.6	17.1
9.....	714	33.970	53 15.94	15.4	16.9
10.....	742	34.393	52 16.45	15.6	17.0
11.....	749	34.469	53 28.57	16.0	17.4
12.....	769	34.707	53 21.37	16.3	17.0
13.....	783	34.905	53 3.42	14.3	14.9
14.....	.....	35.35	52 50.8	15.9	17.2
15.....	881	36.140	52 52.59	16.0	16.9
16.....	892	36.344	52 47.33	15.3	15.7
17.....	901	36.408	52 2.74	15.0	16.8
18.....	944	37.116	53 8.76	15.7	16.8
19.....	950	37.178	52 28.92	15.5	17.1
20.....	985	37.660	53 27.22	15.1	16.5
21.....	1052	38.665	53 1.13	16.5	17.4
22.....	1092	39.538	53 9.70	16.3	16.9
23.....	1193	42.194	51 59.27	15.7	16.8

No. 12.—The variable is the following component of a close double.

No. 16.—The variable is one of a group of stars whose images are partly superposed. The variation is very definite, though small; it would probably be measured much larger if the variable could be isolated.

No. 17.—The variable is the most southern member of a triplet.

No. 19.—Two or three faint companions precede the variable. Von Zeipel thought the image irregular in form.

No. 21.—The variable is the northern, following component of a double.

No. 23.—Von Zeipel's No. 1193 is a close double, two minutes of arc distant from the center of the cluster. The variable, which is the preceding

component, is brighter than its companion at maximum and fainter at minimum. It is not certain that the companion does not also undergo an appreciable variation.

It is to be noted that one-third of the new variables are equal to or fainter than $17^m.0$ at minimum. The faintest minima observed by Bailey were $16^m.9$, and he has suggested that the apparent absence of variables among the thousands of fainter stars is probably real. It is not possible from the data now available, beyond the evidence of the above table, either to support or to oppose this hypothesis, but in the next observing season it is proposed to secure plates that will definitely decide the matter. The light-curves and periods have of course not been determined for the new variables, but they are presumably analogous to those derived by Bailey for stars more distant from the center.

Table II contains the data relative to the stars suspected of light-variation. The arrangement is the same as in Table I, and the notes explain some of the individual cases.

TABLE II

STARS SUSPECTED OF VARIATION

No.	Von Zeipel's Number	α 1900	δ 1900	Magnitude	
				Maximum	Minimum
		13^h37^m	$28°$		
1	604	$32^s.497$	$53'16''.29$	16.5	16.8
2	624	32.806	52 42.25	.....	.....
3	.....	32.97	52 52.1	16.0	16.5
4	666	33.323	53 14.79	16.3	16.6
5	702	33.866	52 28.34	15.5	15.8
6	705	33.878	53 30.93	15.5	16.0
7	712	33.952	53 4.89	15.7	16.5
8	720	34.119	52 30.95	.....	.....
9	894	36.362	53 52.23	.....	.....
10	1007	38.036	53 49.59	16.5	16.9
11	.....	38.58	53 32.8	.....	.....
12	1106	39.988	52 38.22	17.2	17.6
13	1142	40.867	53 18.31	.....	.....

NOTES ON THE INDIVIDUAL STARS IN TABLE II

No. 2.—Von Zeipel's 624 is a triplet. It is difficult to tell which of the stars varies, but it is probably the following component.

No. 7.—The suspected variable is one or other of the two brightest stars in the composite mass catalogued as No. 712.

No. 8.—This star is apparently somewhat out of the position given by von Zeipel. It was at the limit of measurement on his plates. The variability is doubtful.

No. 9.—This extremely close double is Bailey's variable No. 2. It is almost certain that both components are variable. The preceding component varies through a range of a magnitude at least.

No. 10.—The suspected star is the faint preceding companion to von Zeipel's No. 1007, for which the position is given in the table.

No. 12.—A defective image may be the cause of the suspected variability.

No. 13.—The suspected star is the closest of the two faint preceding companions to von Zeipel's No. 1142, for which the position is given in the table.

Several variables of Bailey's list, which were found by him to be difficult of separation from surrounding stars or which for other reasons could not be studied or definitely proved variable, were examined on the Mount Wilson plates. The results are collected in the following notes. The numbers are those assigned in *Harvard Annals*, **78**.

No. 2.—See the reference to this star in the note on No. 9 in Table II above. Only a very small range was observed at Harvard and no period was derived.

No. 4.—This relatively bright star was suspected of a small variation at Harvard. Mount Wilson plates show a variation from $14^{m}.0$ to $15^{m}.3$.

Nos. 8, 30, 73, 95, 98, 127, 129, and 130, all of which are stars concerning whose light-variability there is some question, show no appreciable variation on the Mount Wilson plates.

The suspected variability of No. 99 is definitely confirmed.

The variability of No. 122, doubted by Bailey, is established. The star is a close triplet and the variable is apparently the following, southern component.

Nos. 135 and 136.—Bailey writes concerning both of these stars, which are near the center of the cluster and difficult, that the variation, if genuine, is very small, though when first examined the stars seemed to vary. For the former the variation measured at Mount Wilson is from $15^{m}.3$ to $16^{m}.8$, and for the latter from $15^{m}.7$ to $16^{m}.6$.

MOUNT WILSON SOLAR OBSERVATORY
August 13, 1914

ON THE NATURE AND CAUSE OF CEPHEID VARIATION[1]

By HARLOW SHAPLEY

The purpose of the present discussion is an attempt to investigate the question of whether or not we should abandon the usually accepted double-star interpretation of Cepheid variation. In addition to the brief statement of some general considerations and correlations of the many well known characteristics of Cepheid and cluster variables, certain recently discovered properties of these stars are discussed in greater detail, because chiefly upon them are based the conclusions reached in this study.

It seems a misfortune, perhaps, for the progress of research on the causes of light-variation of the Cepheid type, that the oscillations of the spectral lines in nearly every case can be so readily attributed, by means of the Doppler principle, to elliptical motion in a binary system. The natural conclusion that all Cepheid variables are spectroscopic binaries has been the controlling and fundamental assumption in all the recently attempted interpretations of their light-variability, and the possibility of intrinsic light-fluctuations of a single star has received little attention.

From the very first there have been serious troubles with each new theory. Considered from the spectroscopic side alone, the Cepheids stand out as unexplainable anomalies. There are persistent peculiarities in the spectroscopic elements, such as the low value of the mass function, the universal absence of a secondary spectrum, and the minute apparent orbits. Practically the only thing they have in common with ordinary spectroscopic binaries is the definitely periodic oscillation of the spectral lines, which permits, with some well known conspicuous exceptions,[2] of

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 92. Read at the seventeenth meeting of the American Astronomical Society, August 1914.

[2] The irregularities in the velocity-curve of ζ Geminorum have been discussed by Campbell (*Astrophysical Journal*, **13**, 94, 1901), Russell (*Astrophysical Journal*, **15**, 260, 1902), and Plummer (*Monthly Notices*, **73**, 661, 1913). The deviations from purely elliptical motion in the case of W Sagittarii have been considered by Curtiss (*Lick Observatory Bulletins*, **3**, 36, 1904; *Astrophysical Journal*, **20**, 149, 1904); in the

interpretation as periodic orbital motion. Adding, then, to the spectroscopic abnormalities the curious relations between light-variation and radial motion, the difficulties in the way of all the proposed simple solutions seem insurmountable. Geometrical explanations of the light-variation fail completely, and little better can be said of the hypotheses that involve partly meteorological and partly orbital assumptions.

The writer can offer no complete explanation of Cepheid variability as a substitute for the existing theories that are shown to be more and more inadequate. At most, only the direction in which the real interpretation seems to lie can be pointed out, and an indication given of the strength of the observational data that would support the theory developed along the lines suggested. The principal results of a rather extensive investigation, further details of which it is hoped can be published in subsequent papers in the near future, are outlined in the following paragraphs. The main conclusion is that the Cepheid and cluster variables are not binary systems, and that the explanation of their light-changes can much more likely be found in a consideration of internal or surface pulsations of isolated stellar bodies.

THE ESSENTIAL IDENTITY OF CEPHEID AND CLUSTER VARIABLES

The subdivision of the short-period variables into the cluster type and the Cepheid type is an artificial one. This proposition scarcely needs proof, although the assumption of the essential similarity of the two groups is important in the following discussion. Practically all writers on the subject are more or less inclined to accept this view.[1] The definition of the cluster-type variable is,

case of Y Ophiuchi by Albrecht (*Lick Observatory Bulletins*, **4**, 134, 1907) and later by Zurhellen (*Astronomische Nachrichten*, **177**, 329, 1908) and Miss Udick (*Publications of the Allegheny Observatory*, **2**, 151, 1912); in the case of RT Aurigae by Duncan (*Lick Observatory Bulletins*, **5**, 120, 1909). For many Cepheids the total range of velocity variation is so small that secondary oscillations and other irregularities of considerable relative importance may easily be lost in the accidental errors (Curtiss, *op. cit.*, p. 39).

[1] See, for instance, Nijland, *Hemel en Dampkring*, April 1913; Williams, *Journal of the British Astronomical Association*, **23**, 134, 1912; Kiess, *Publications of the Astronomical Society of the Pacific*, **24**, 191, 1912, and **25**, 121, 1913; Townley, *Publications of the Astronomical Society of the Pacific*, **25**, 239, 1913.

in fact, by some merely "short-period Cepheid." Others, including Hartwig[1] and Kron,[2] have considered only those with rapidly decreasing brightness and constant light at minimum as "antalgol" or cluster-type variables. Kron calls the shortest-period variable known a Cepheid,[3] and Hertzsprung[4] designates as Cepheids only those variables whose periods are greater than a day. The writer proposes to adopt, merely as a convenience, the latter practice, arbitrarily calling the Cepheids of periods less than a day cluster-type variables; for there is at present no evidence of real difference between the two classes in the nature or probable causes of the light and velocity variations.[5] Hertzsprung[6] calls attention to the maxima in the frequency-curve of the periods at twelve hours and at seven days, and notes also that the longer-period Cepheids are

[1] *Vierteljahrsschrift der Astronomischen Gesellschaft*, **37**, 284, 1902.

[2] *Publikationen des Astrophysikalischen Observatoriums zu Potsdam*, **22**, Pt. III, 53, 1912. See also Newcomb-Engelmann, *Populäre Astronomie*, 5th ed., p. 623, Leipzig, 1914.

[3] XX Cygni, period 3^h14^m.

[4] *Astronomische Nachrichten*, **192**, 262, 1912.

[5] It is hardly necessary to remark that Cepheids and Geminids are physically identical. The latter term merely signifies that the rise and decline of brightness require approximately equal intervals of time. There are numerous types of variation intermediate between the chosen typical curves of ζ Geminorum and δ Cephei. A significant feature that has not been pointed out explicitly heretofore is that the smaller the ratio of interval of increasing light to interval of decreasing light the greater the eccentricity. Orbits of Geminids therefore have smaller eccentricities. This really amounts to observing that the light-curves and velocity-curves of all classes of Cepheids are generally identical in form. See the study by Luizet, "Les Céphéides considérées comme étoiles doubles," *Annales de l'Université de Lyon*, Nouvelle Série, I, Fascicule 33, 67–148, 1912.

Some Geminid curves, however, permit of hypothetical interpretations that cannot be applied to the more typical Cepheid. Russell has found (*Popular Astronomy*, **22**, 142, 1914) that, if the time of rise to maximum is greater than one-fourth the period, the light-variations may be interpreted as the rotation of a spotted body, but such an explanation is otherwise untenable. The writer has shown (*Laws Observatory Bulletin*, **2**, 71, 1913; *Astronomische Nachrichten*, **194**, 353, 1913) that for certain symmetrical curves of the Geminid type the light-variations may be due entirely to the rotation of a single ellipsoidal star. This explanation is a possible and plausible one, but for SZ Tauri, one of the stars suitable for such an interpretation, Haynes has found a typical Cepheid velocity variation (*Lick Observatory Bulletins*, **8**, 85, 1914).

[6] *Astronomische Nachrichten*, **179**, 376, 1909; **192**, 262, 1912; **196**, 205, 1913. Chandler reached some of the same conclusions twenty-five years ago (*Astronomical Journal*, **9**, 1, 1889).

in the galaxy, while the shorter-period Cepheids or cluster variables are apparently distributed more at random over the sky. Making the reasonable assumption that the data, though rather meager, are sufficient, nevertheless, to establish the reality of both phenomena, these conditions do not impeach the hypothesis that the light and velocity variations of the long- and short-period Cepheids are attributable to the same causes, and that the only modifications necessary in an explanation of one, to make it applicable to the other, are those depending on the length of the periods and other gradative characteristics, such as differences of spectral type and relative speed of light-change at corresponding phases. Among the several arguments that tend to prove the inherent similarity of the two groups of Cepheids, the following are the most important.

a) For RR Lyrae, period 13.6 hours, which is commonly classified as a cluster-type variable, the spectroscopic orbit by Kiess[1] resembles in all details the peculiar orbits characteristic of the longer-period Cepheids. The light-curve is typical of cluster variables in all its properties.[2]

b) From the photometric standpoint, Graff and Bottlinger[3] have found no essential differences between light-curves of cluster and Cepheid types, and insist on the artificiality of the division into two classes. Very few, if any, of the cluster-type variables have rigorously constant light at minimum phase, as Plummer,[4] among others, has shown. In fact, it was partly for this reason that Hartwig abandoned, in the *Vierteljahrsschrift* catalogue, the former term "antalgol" and the former distinction between cluster and Cepheid variables.[5]

c) Russell's harmonic analyses of the mean light-curves of typical cluster variables and typical Cepheids indicate the necessity of analogous interpretations of the two.[6]

d) An unpublished investigation by the writer of the relation between the periods and spectral types of all variables shows the

[1] *Lick Observatory Bulletins*, **7**, 140, 1913.

[2] Kiess, *Publications of the Astronomical Society of the Pacific*, **24**, 189, 1912.

[3] *Astronomische Nachrichten*, **196**, 113, 1913. [4] *Monthly Notices*, **73**, 657, 1913.

[5] *Vierteljahrsschrift der Astronomischen Gesellschaft*, **48**, 287, 1913.

[6] An abstract is printed in *Popular Astronomy*, **22**, 142, 1914.

existence of a continuous property from the longest-period Cepheids to the shortest-period cluster variables.

e) The shift of the maximum intensity in the spectra toward the violet with increasing light is a property common to both classes.[1]

IRREGULARITIES IN THE LIGHT-ELEMENTS

Starting, then, with the apparently well-grounded assumption that the reasoning relative to the nature of the cluster-type variation applies equally well to Cepheid variation, the first argument presented against the binary character of Cepheids deals with the irregular oscillations in the photometric period. In a paper presented to the American Astronomical Society at its last meeting, the writer reported on the oscillations in the periods of several cluster-type stars.[2] The study of such irregularities must necessarily, for the present at least, be confined to photometric observations, for the faintness of the stars, and the consequent length of spectroscopic exposure would conceal irregular oscillations in the velocity measurements.[3] The investigation, as is also obvious, must succeed first with the stars of shortest period, for with them the light-change is of sufficient rapidity to permit the determination of points on the steep ascending branch of the light-curve with high precision.

Further observations of SW Andromedae, made since the last report, have confirmed the previous results, showing that the time of the rise to maximum light varies from the mean predicted time by ten or fifteen minutes within the short interval of two or three days, but evidently without exhibiting regular periodicity. The uncertainty of the determination does not exceed three or four minutes. The similar oscillations in the light-curve of RR Lyrae

[1] For the Cepheids see the work of Albrecht (*Lick Observatory Bulletins*, **4**, 131, 1907) and of other Lick observers. For the cluster-type variables see the work of Kiess, referred to above, and the indirect determinations of the maximum intensity shifts presented in a later section of the present paper.

[2] An abstract is printed in *Popular Astronomy*, **22**, 144, 1914.

[3] The average length of exposure on RR Lyrae with a one-prism spectrograph attached to the 36-inch refractor of the Lick Observatory was more than two hours—nearly one-sixth of the entire period. RR Lyrae is the brightest cluster variable known (excepting β Cephei).

were apparently periodic throughout the interval of two or three years covered by the earlier series of Harvard observations,[1] but the later work at Harvard[2] and at the Lick Observatory[3] shows a different amplitude and perhaps no periodicity at all. The Lick and Harvard observations were made with visual photometers. In a recent letter Professor Hertzsprung writes that he also finds irregularities from night to night in photographic observations of the star.

The oscillation in the time of brightening to maximum seems to be a pretty general characteristic, though possibly not universal. It is shown definitely for several other stars besides those mentioned above,[4] and perhaps most noticeably in the case of XX Cygni, which is discussed in the next section. The most remarkable feature of the oscillation, which from night to night is conspicuously large in some cases, is that a change in the mean period of the light-variation has been recorded for only two stars, and these changes are relatively minute.[5] If the observed oscillations were definitely periodic, it would perhaps be possible to attribute them in some kind of a binary system to orbital changes, such as the rotation of the line of apsides. But the sudden and unpredictable changes in the light-variation, very likely accompanied by analogous oscilla-

[1] *Harvard Annals*, **69**, Pt. I, 45, 1909.

[2] The manuscript of these observations was kindly sent to the writer by Professor Pickering; more recently the work has been published in *Harvard Annals*, **69**, Pt. II, 124, 1913.

[3] *Lick Observatory Bulletins*, **7**, 141, 142, 1913.

[4] *Popular Astronomy*, **22**, 144, 1914.

[5] According to Kron the mean period of XX Cygni is decreasing by about a tenth of a second a year (*op. cit.*, p. 47). Roberts finds that the mean period of S Arae is decreasing by four-hundredths of a second a year (*Astrophysical Journal*, **33**, 200, 1911). The long-accepted secular change in the period of δ Cephei, first established with some uncertainty by Chandler (*Astronomical Journal*, **13**, 101, 1893) and later maintained by Nijland (*Astronomische Nachrichten*, **161**, 229, 1903), has recently been completely rejected by Luizet in his monograph on the light-variations (*Annales de l'Université de Lyon*, Nouvelle Série, Fascicule 33). Belopolsky, however, finds an oscillation in the spectroscopic period (*Mitt. Pulk.*, **3**, 63, 1909). W. J. S. Lockyer has found (Dissertation, Göttingen, 1896) that, while the mean period of η Aquilae is constant, there is an oscillation in the epoch of maximum through an amplitude of ten hours. Hellerich (Dissertation, Berlin, 1913) has studied the periods of ten Cepheids and finds no necessity of second-order terms.

tions in the velocity-curve, introduce another difficulty into the binary system theory.

IRREGULAR CHANGES IN THE LIGHT-CURVES

The second argument against the double-star explanation of Cepheid variation lies in the continually changing form of the light-curves from one maximum to the next. Again we will consider mainly the cluster-type stars. For the Cepheids the length of the period prohibits, in general, continuous observations throughout successive epochs, and in the long run the irregularities smooth out in a mean light-curve. Curtiss[1] has noticed, however, that the light-curve of W Sagittarii, period 7.6 days, changes shape with the time, and similar results are suggested for other Cepheids by various observers.[2] For the stars with periods less than a day, however, many long series of observations have been made, and although the work was rarely if ever undertaken for the purpose of seeking short-period changes in the form of the light-curve, nevertheless irregularities have often been found. Many observers have noticed that the errors are larger in observing short-period variables than in any other class. Roberts[3] and Innes[4] were suspicious of the large deviations in their measures of S Arae. Sperra[5] concluded from an extensive treatment of his visual observations on SW Draconis and SU Draconis that the shapes and durations of both maxima and minima varied from night to night. This was, I believe, the first and only serious attempt that has been made to question the supposed clocklike precision of short-period variation. Plummer and Martin[6] are disinclined to accept Sperra's results without further proof, for the photographic observations at Dunsink (exposure times from thirty minutes to an hour) do not confirm such irregularities (though they do show remarkable irregularities,

[1] *Lick Observatory Bulletins*, **3**, 168, 1905.

[2] For instance, the light-curve of δ Cephei, as pointed out by Luizet (*op. cit.*, pp. 58–60).

[3] *Astrophysical Journal*, **33**, 201, 1911.

[4] *Annals of the Cape Observatory*, **9**, 126B, 1903.

[5] *Astronomische Nachrichten*, **184**, 241–252, 1910.

[6] *Monthly Notices*, **73**, 440, 1913.

supposedly permanent, in the mean curves). The proof is now at hand, however, and with amazing clearness in the observations of XX Cygni, published at Potsdam.[1] The three-hour period of this star is obviously a great advantage in the study of the changing form of the light-curve. If the variations of SW Andromedae and RR Lyrae referred to above could have been followed regularly throughout their entire periods, there is little doubt that the oscillations in the time of the rise to maximum would have been found to constitute only a part of the irregularities.

In his discussion of nearly three thousand observations of XX Cygni, Kron finds a small secular change in the mean period, but does not consider real the deviations from the mean curves. The observations of ten observers are included. Both Schwab and Guthnick considered the irregularity of form a real phenomenon, and the former notes that, while the maximum and minimum magnitudes remain sensibly constant, the times between the ascent and descent past magnitude 11.2 vary from 35 minutes to an hour.[2] A study of the observations shows the same phenomenon in the work of all the observers.[3] The various forms of light-curve cannot be attributed to night errors. The differences between the curves at different epochs is distinctly larger than the errors of the observations. This is particularly true for Kron's photometric work. The average deviation of his measures from a normal curve, based on his own observations, is much larger than that of measures on the comparison stars, and probably more than twice as large as the average deviation of the observations from separate nightly curves. There appears, however, to be no definite periodicity in the changing shape of the curve; as a rule sharp maxima follow each other

[1] *Publikationen des Astrophysikalischen Observatoriums zu Potsdam*, **22**, Pt. III, 1912.

[2] *Astronomische Nachrichten*, **170**, 369, 1906.

[3] This and other points relative to the anomalies of the light-variation will be discussed more fully in a later communication. Contrary to all other experience with Cepheid variables the photographic range measured by Parkhurst and Jordan (*Astrophysical Journal*, **23**, 84, 1906) is less than the visual range. To examine this question more closely a series of simultaneous photographic and photovisual observations has recently been made with the 60-inch reflector. This will furnish a definitive color-curve, as well as serve as a control on the secular change in the period. (Parkhurst and Jordan also suspected oscillations in the period; *op. cit.*, p. 86.)

for a few days, to be succeeded by an intermediate type and then by a series of relatively wide, flat-topped maxima. Sometimes the extreme change in form occurs on successive nights. In the variations of the light-curve, as in the oscillations of the time of the rise to maximum light, the regularity and continuity of the phenomena that would be demanded by an orbital explanation is apparently lacking.

CHANGES IN COLOR AND SPECTRAL TYPE

A third argument against the binary interpretation of Cepheids is the difficulty such theories would have in explaining the periodic change of the spectral type, though it must be admitted that to a certain extent Duncan's hypothesis,[1] if otherwise acceptable, could account for spectral changes through the medium of atmospheric absorption. The evidences of the change of spectral type with changing light, though not well known nor generally recognized, are decisive and important. Schwarzschild,[2] Wirtz,[3] and more particularly Wilkens[4] have demonstrated for Cepheids of longer period that the range of light-variation is greater in the photographic than in the visual part of the spectrum. The photographic work of Martin and Plummer[5] suggests similar results for cluster-type variables, while the recent simultaneous photographic and photovisual observations by Mr. Seares and the writer at

[1] *Lick Observatory Bulletins*, **5**, 91, 1909; *Publications of the Astronomical Society of the Pacific*, **21**, 123, 1909.

[2] *Publikationen der v. Kuffnerschen Sternwarte*, **5**, C100, 1900. The photographic range of η Aquilae is found to be double the visual range. More recently Kohlschütter has repeated the photographic work and finds that the color-curve has an amplitude of four-tenths of a magnitude (*Astronomische Nachrichten*, **183**, 265, 1910).

[3] *Astronomische Nachrichten*, **154**, 327, 1901. Wirtz measures the photographic ranges of δ Cephei and ζ Geminorum.

[4] *Astronomische Nachrichten*, **172**, 316, 1906. An average value of 1.6 is found by Wilkens for the ratio of photographic to visual range for the Cepheid variables SU Cygni, X Cygni, T Vulpeculae, S Sagittae, and U Vulpeculae. The visual ranges, it should be remarked, are collected by him from various sources and can hardly be considered homogeneous or reliable. The results, however, are qualitatively dependable, but more work along this line is desired. The Cepheids mentioned in the three last notes are of spectral types F to K5, with an average very close to the solar type.

[5] SU Draconis, *Monthly Notices*, **73**, 166, 1912; SW Draconis, *ibid.*, **73**, 440, 1913; Cygni, *ibid.*, **74**, 225, 1914.

Mount Wilson establish the fact definitely.[1] The shift of the maximum intensity in the spectra of Cepheids, discovered by Albrecht,[2] has been confirmed by Kiess[3] and other Lick observers. These two factors—the greater photographic range and the shift of the maximum intensity—would suggest as an underlying and common cause a change in the spectral type. Albrecht and Duncan[4] have observed that Wright's spectrograms of η Aquilae suggest a later type of spectrum at minimum than at maximum. The Harvard classification of TT Aquilae[5] at maximum is G, at minimum, K.

For the cluster-type variables there is more direct evidence of distinct and continuous change. At the writer's request Miss Cannon has examined some of the Harvard spectrograms of certain cluster variables. For RR Lyrae no definite change was recorded on the plates examined, and similarly for XZ Cygni, but the spectrum, when faint, was extremely uncertain. For SW Andromedae the spectrum was of type A at maximum and clearly of a redder type at minimum. The most conclusive results, however, are obtained from the series of spectrograms taken by Mr. Pease[6] in July of this year with the 60-inch reflector of the Mount Wilson Observatory. The variable RS Boötis, period $9^h.1$, shows a continuous change of spectral type from Fo at minimum to B8 at maximum. One consequence of this result is that hereafter the classification of all Cepheid and cluster-type spectra must be made with due specification of the corresponding phase of light-variation.[7]

[1] A report on this work was presented at the meeting of the American Astronomical Society at Evanston, Illinois, August 25–28, 1914.

[2] *Lick Observatory Bulletins*, **4**, 131, 1907. [3] *Ibid.*, **7**, 140, 1913.

[4] *Ibid.*, **5**, 93, 1909. [5] *Harvard Annals*, **55**, 285, 1909.

[6] A report on this work was presented at the meeting of the American Astronomical Society at Evanston, Illinois, August 25–28, 1914.

[7] Miss Clerke writes: "The spectrum [of δ Cephei] is of the solar type, and does not change with the brightness" (*Problems in Astrophysics*, p. 320, London, 1903). This, however, should not discourage new attempts to classify the spectrum of the type-star and of other longer-period Cepheids at various phases of their light-changes. It is possible, of course, that the changes in color index and shifts of maximum intensity are not generally accompanied in the longer-period Cepheids by those changes in the absorption lines that are necessary to give a different spectral classification under the present system, in which the absorption lines receive much attention and the background intensities but little. But in the early study of the spectrum of δ Cephei, published by Belopolsky in *Bulletin*, No. 3 of the Imperial Academy of Sciences of

Another difficulty in the spectral changes, that must not be overlooked in attempting a complete explanation of the Cepheid phenomena, is a peculiarity observed by Albrecht[1] on his plates of Y Ophiuchi and T Vulpeculae. Various lines showed large irregular shifts, which are not progressive with the phase of the star in its light-period.

CONCERNING EXISTING HYPOTHESES

The fourth principal argument against the binary interpretation of Cepheids is the inadequacy of all the existing double-star hypotheses. To many this is not only the best argument but is sufficient in itself.[2] A detailed criticism of these attempted explanations is unnecessary, for this has been generously provided by the proposers of the theory themselves, as well as by others, including Campbell,[3] Plummer,[4] Brunt,[5] Kiess,[6] and Ludendorff.[7] There is

St. Petersburg, 1894, the variations in the relative intensities of several lines are suggested and certain deviations from the solar spectrum are explicitly pointed out on many spectrograms. The question is one to be answered definitely by future researches. (A very recent study of the changes in the spectra of δ Cephei and ζ Geminorum has been made at St. Petersburg by Lohmann, but the paper is not yet available to the writer.)

[1] *Lick Observatory Bulletins*, **4**, 131–132, 1907.

[2] There has been a growing and but half-concealed discontent with the double-star explanations of Cepheids. Ludendorff writes (*Astronomische Nachrichten*, **193**, 304, 1912): "Freilich kann man sich aus verschiedenen Gründen des Eindrucks kaum erwehren, dass die in den Spektren der δ Cephei-Sterne beobachteten periodischen Linienverschiebungen nicht durch Radialbewegungen der Sterne, sondern durch irgendwelche andere Ursachen hervorgerufen werden." On the other hand, Paddock interprets Ludendorff's data in a manner favorable to Duncan's double-star hypothesis (*Publications of the Astronomical Society of the Pacific*, **25**, 180, 1913).

Plummer considers, in a recent paper on the nature of the Doppler principle when based on the Ritz theory of light, the possibility of getting around the difficulties presented by the velocity variations of certain variables (obviously Cepheids are meant) by abandoning the binary interpretation altogether, but he is led rather to abandon the Ritz theory (*Monthly Notices*, **74**, 660, 1914). Until the velocity variation of RR Lyrae was discovered he was inclined to suggest that cluster-type variation might be "a prominence effect on a large scale" (*ibid.*, **73**, 658, 1913).

[3] *Stellar Motions*, pp. 305 ff., New Haven, 1913; *Lick Observatory Bulletins*, **6**, 51, 1910.

[4] See various papers cited above. [5] *Observatory*, **36**, 59, 1913.

[6] *Publications of the Astronomical Society of the Pacific*, **24**, 186, 1912; see also other papers cited above.

[7] *Astronomische Nachrichten*, **184**, 384, 1910.

one point, however, that has not been considered, which is of prime importance in the discussion of Cepheid phenomena. Russell[1] and Hertzsprung[2] have independently shown that the Cepheids are stars of small peculiar motions and small parallaxes, and hence of great absolute brightness. The former finds a mean absolute magnitude of -2.4 and the latter of -2.3, that is, the average Cepheid (the spectrum is of solar type) is nearly 700 times as bright as the sun. It is reasonable to assume that the Cepheids and the sun have a comparable surface brightness. The average Cepheid, then, has a volume between fifteen and twenty thousand times as great as that of the sun.

Interpreted as spectroscopic binaries these giant stars move in orbits whose apparent radii average less than one-tenth the radii of the stars themselves.[3] In order that the radii of the real orbits may greatly exceed those of the apparent orbits, the inclinations must be very small, a condition which cannot be supposed to exist generally for Cepheid orbits. The difficulty in applying the hypotheses of Eddie,[4] Loud,[5] Duncan,[6] and Roberts[7] is therefore immediately apparent. Moreover, if the mass of the average Cepheid is admitted to be as much as five times the solar mass, the density is still astonishingly low—hardly three ten-thousandths that of the sun. Considering the low average value of the mass function[8] derived from the orbits of the Cepheids, and taking a random distribution of the orbital inclinations, the non-luminous second body, to which Duncan's theory assigns the extensive atmosphere that must envelope the giant primary, has about one-tenth of the mass and therefore must move with an average apparent

[1] *Science*, N.S., **37**, 652, 1913.

[2] *Zeitschrift für wissenschaftliche Photographie*, **5**, 107, 1907; *Astronomische Nachrichten*, **196**, 201, 1913.

[3] The average value of $a \sin i$ for 15 Cepheids is 1,116,000 km. The greatest value is 2,000,000 km, and the least is 45,000 km.

[4] *Astrophysical Journal*, **3**, 227, 1896. [5] *Ibid.*, **26**, 369, 1907.

[6] *Lick Observatory Bulletins*, **5**, 91, 1909.

[7] *Astrophysical Journal*, **33**, 197, 1911; *Monthly Notices*, **66**, 329, 1906.

[8] The average value of $\frac{m_1 \sin^3 i}{(m_1+m)^2}$ for 15 Cepheids is 0.0025. The greatest value is 0.0058, and the least is 0.00001 for Polaris.

orbital velocity of about 200 km a second. Remembering the size of the primary star compared with its orbit, we know that the mass of the secondary must be still smaller and the velocity higher to separate the stars.

A SUGGESTED EXPLANATION OF CEPHEID VARIATION

In the face of all these difficulties, it seems appropriate to abandon completely the attempts to interpret Cepheids on the basis of a binary-star assumption. It has been shown by Russell[1] that the light-variations cannot be explained satisfactorily by the uniform rotation of a single spotted star; the light-change must be intrinsic, and not just apparent. The explanation that appears to promise the simplest solution of most, if not all, of the Cepheid phenomena is founded on the rather vague conception of periodic pulsations in the masses of isolated stars. The vagueness of the hypothesis lies chiefly in our lack of knowledge of the internal structure of stellar bodies, and not in the difficulty of explaining the observed facts if once we assume the stars to be ideally gaseous figures of equilibrium. Moulton[2] has considered the matter of explaining certain types of stellar variation from this point of view, but his conclusions are scarcely applicable to Cepheid variables in the light of our present knowledge of their peculiar properties.[3] According to him, the light-change should be due to the heat generated by the oscillation of a spherical star from an oblate to a prolate form, there being a maximum of light-emission every time the star passes through its mean spherical figure. The period of velocity variation, then, should be double that of the light-change,[4] and

[1] *Popular Astronomy*, **22**, 142, 1914. See the footnote on a preceding page relative to this work. Russell's investigation, then, opposes the explanation suggested by Hellerich (Dissertation, Berlin, 1913).

[2] *Astrophysical Journal*, **29**, 257, 1909.

[3] The hypothesis also is not obviously applicable as a complete or even partial explanation of the variation of elliptical eclipsing binaries, considering the present state of the orbital theory. The presence of the secondary spectrum, the very large periodic shift of the spectrum lines, and many other factors are almost unimpeachable proofs of the binary character of eclipsing variables. Very little if any effect on the light-variation can be attributed in any of the systems studied to pulsations, or even to tidal disturbances.

[4] That is, if the shift of the spectrum lines is to be attributed to a radial motion of the source.

this, of course, does not conform with known conditions.[1] It is to this phenomenon of pulsating stellar masses, however, that the writer would ascribe the light and velocity variation of Cepheid and cluster variables, and the theoretical work of Moulton,[2] Jeans,[3] Emden,[4] and others[5] on the properties of gaseous spheres already justifies the conclusion that such oscillations are both possible and probable. They might arise, as Moulton suggests, from the collision with masses of only planetary dimensions, from the near approach of two stars, or in other ways.[6]

Without any pretense of explaining clearly or fully on this hypothesis all the properties of Cepheid variation that have given the double-star theories such hopeless difficulty, a few points favoring the pulsation suggestion will be summarily stated. There will exist originally, as the result of the initial disturbance, a great number of oscillations with different periods. The character of these various vibrations will depend on the nature of the stellar structure. For the ideal homogeneous fluid mass investigated by Kelvin,[7] and for the polytropic gaseous sphere defined and studied by Emden,[8] the period of vibration of each type is independent of the volume and mass and depends only on the mean density and the order of the harmonic term defining the oscillation.[9] For any given

[1] It is well to keep in mind, however, the secondary maxima in the light-curves of η Aquilae and similar variables. Therein perhaps is a visible trace of the secondary heating of each oscillation period.

[2] *Op. cit.*

[3] *Philosophical Transactions of the Royal Society of London*, **199 A**, 1, 1902; *ibid.*, **201 A**, 157, 1903; *ibid.*, **213 A**, 457, 1914.

[4] *Gaskugeln*, Leipzig, 1907.

[5] The numerous papers by Ritter, *Wiedemanns Annalen*, **5–20**, 1878–1883, are of fundamental importance in this problem. His consideration of vibrational variable stars has been briefly discussed by Moulton (*op. cit.*).

[6] Perhaps then we should expect to find great numbers of these variables in condensed regions, such as the globular clusters and the Magellanic clouds.

[7] *Mathematical and Physical Papers*, **3**, 384, 1890. [8] *Op. cit.*, pp. 13, 37, 448 ff.

[9] The vibration period in seconds is for the former

$$\tau = 2\pi\left(\frac{2m+1}{2m(m-1)}\right)^{\frac{1}{2}}\left(\frac{R}{G}\right)^{\frac{1}{2}}$$

and for the latter

$$\tau = 2\pi\left(\frac{R}{mg}\right)^{\frac{1}{2}}$$

where m is the order of the spherical harmonic defining a given oscillation, R is the radius, and g, the surface gravity, is proportional to radius times mean density.

mean density the most important oscillation is that corresponding to the second-order harmonic. Its period is the longest, its amplitude the greatest, and it may persist with inappreciable change in period almost indefinitely, while the oscillations of higher order are more rapidly destroyed by friction.

If, then, we attribute the principal light-change in a Cepheid variable to this principal oscillation, and if we are willing to adopt Emden's polytropic gaseous sphere as a stellar model, we can compute at once the density of each individual variable. Obtained in this way the densities are probably of the right order of magnitude, whatever function of the radius, within reasonable limits, the density is assumed to be; and for an incompressible homogeneous fluid they would be only 2.5 times as large. The densities in terms of the sun for all the Cepheids of known periods and spectra[1] have been derived in this manner, with the results given in Table I.[2]

[1] It is impossible to say, of course, whether the spectra listed were obtained near maximum or near minimum. Errors in the grouping, for the brighter Cepheids at least, will probably balance in the means.

[2] The data for this computation have been derived mainly from *Harvard Annals*, **56**, 191–195, 1912. In the table of "short-period variables" given in that publication are included many stars that are now known to be eclipsing binaries. It is very likely that further study will show that others are not Cepheids, but in the means in Table I are included all variables not known to be eclipsing stars.

The densities in the table are computed for the mean periods of each class. If the means of the individual densities were taken one badly discordant period would greatly distort the result.

A striking fact shown by Table I is the progressive relation between spectrum and period, and hence, between spectrum and density. "The redder the tint, the longer the period" was observed by Chandler in 1888, but referred mainly to long-period variables (*Astronomical Journal*, **8**, 137, 1888). He called attention to the importance of this correlation to variable star hypotheses. Campbell noticed that "the length of periods seems to increase with the spectral types, but the relationship is not strongly marked" (*Lick Observatory Bulletins*, **6**, 51, 1910).

Russell's theory of the order of stellar evolution is supported by the results of Table I when we remember that the Cepheids are giant stars. For it is obviously fair to conclude from the progression of the densities that, if the present Cepheid hypothesis approximates the truth, the order of evolution is in the direction from type M to type B. The Cepheids then are young stars. Perhaps the long-period redder variables of the Mira Ceti type, with spectra of types M*a*,....M*d*1, M*d*2,....M*d*10, N, etc., are still earlier in their evolution. Are they merely Cepheids of very long period? In many respects they appear to be—the light-curves are similar, the shape and time of successive maxima often oscillate around probably rigorously constant mean values, the spectra change progressively throughout the light-period, and finally

The extremely low densities for the Cepheids of the redder spectral types until recently might have thrown serious doubt on the hypothesis that demands such abnormally low values. But now for two reasons we are ready to accept as possible these supposedly impossible densities. In the first place, as Hertzsprung has pointed

TABLE I

Type	No. Stars	Mean Period	Mean Density
M	3	33	0.000006
K	9	18	0.000020
G	31	11	0.000056
F	31	6	0.000200
A	9	0.4	0.04
B*	1	0.19	0.2

*β Cephei is properly to be assigned to the Cepheid type. Notwithstanding the very short period (4^h5), the preliminary orbit by Frost (*Astrophysical Journal*, **24**, 259, 1906) is typical of the Cepheids. Guthnick's discovery (*Astronomische Nachrichten*, **196**, 357, 1913) of the light-variation and its nature (a typical cluster-variable curve of small amplitude) further supports this classification, and the harmony of the hypothetical density with that for the other groups of Cepheids is probably a third favorable argument. The presence of a second spectrum, however, is suspected on certain plates, according to the preliminary announcement (*Astrophysical Journal*, **24**, 261, 1906).

out[1] in his proof that the Cepheids of solar spectral type are giant stars, the average mean density must be of the order of 6×10^{-5}, if the masses are comparable with that of the sun. They may be larger, but from our knowledge of stellar masses in general we are inclined to believe that they are not more than ten times that of the sun,[2] which is sufficient to prove the point. In the second place, the densities of several long-period eclipsing binaries of types G and K are now available for comparison.[3] For instance: RX Cassiopeiae; type Ko, mean density 5×10^{-4}; W Crucis, type Gp, mean density 3×10^{-6}; SX Cassiopeiae, type G3, mean density 5×10^{-4}; RZ Ophiuchi,[4] type F8, density of one component 10^{-3}.

they are apparently stars of great absolute luminosity. Long ago, however, Chandler gave several good reasons for distinctly separating "long period" and "short period" variables (*Astronomical Journal*, **9**, 1, 1889), and to a certain extent these distinctions are still to be maintained.

[1] *Astronomische Nachrichten*, **196**, 203, 1913 (footnote).

[2] Russell, *Nature*, **93**, 283, 1914; *Popular Astronomy*, **22**, 294, 1914. Ludendorff, *Astronomische Nachrichten*, **189**, 151, 1911.

[3] *Contributions from the Princeton University Observatory*, No. 3, 1914.

[4] The spectrum has been reclassified recently by Miss Cannon at the writer's request. The components are of nearly equal brightness (visually), but it is very likely that the photographic spectrum classified is that of the smaller component which has high relative surface brightness, and density as given above. The density of the fainter component is 2×10^{-5} (*Astronomische Nachrichten*, **194**, 225, 1913).

For the A- and B-type spectra, the Cepheid densities above are, of course, entirely normal compared with eclipsing star densities.[1]

As previously stated, the Cepheids without doubt are enormously large. Their small observed velocity variations, even if attributed altogether to motion in the line of sight and not at all to pressure-shifts, are not larger than might arise from a radial oscillation through but a small fraction of their mean diameters.[2] In the central mass of the star the period of the supposed pulsation should, of course, be perfectly regular, but its effect need by no means be regular on the radiating surface.

We may suppose that, because of the internal vibration, the photosphere of the star is periodically scattered or broken through by the rush of hotter gases from the interior. Maximum light and maximum velocity of approach would obviously be approximately synchronous, and their coincidence would naturally be independent of the direction of the observer in space. Ludendorff's correlation of range of light and range of velocity is highly significant in this connection.[3] The essentially harmonic nature of the oscillation at the surface of the star would easily lend itself to interpretation as elliptic motion, though non-elliptic motion need not be unexpected, nor the anomalous behavior of certain spectral lines. In stars in which the initial disturbance is of recent origin, the presence of secondary oscillations could be expected, which would affect the light as well as the velocity.[4]

It should be noted as an important factor in the explanation of Cepheid variation, that a change in the spectrum of a given radiating surface from one type to the next will change the visual brightness of that surface by approximately one stellar magnitude,

[1] *Astrophysical Journal*, **38**, 173, 1913.

[2] The radial motions observed in sun-spots are suggestive in this connection.

[3] *Astronomische Nachrichten*, **193**, 301, 1913. He finds that $2K = 47.3A$ with close approximation, where A is the amplitude of magnitude variation and $2K$ is the total range of velocity variation in kilometers.

[4] By means of a detailed periodogram analysis of the light-curve of the famous irregular variable SS Cygni, Gibb has recently found a prominent underlying periodicity of 40.86 days (*Monthly Notices*, **74**, 678, 1914). The spectrum of SS Cygni is extremely peculiar in that it varies through a number of different types, occasionally showing bright lines and at other times an apparently continuous spectrum (*Harvard Annals*, **56**, 211, 1912).

and the color range by four-tenths of a magnitude. These quantities correspond very closely to what is observed in cluster variables, and suggest that, if desired, it is unnecessary to go farther for the explanation of the light-variation than to suppose that a surface of approximately constant area progressively changes its spectral type as the result of a periodic flow and ebb of heat.[1] That the light-change should be of a more explosive character for the cluster variables than for the longer-period Cepheids would be expected because of their higher mean densities.

Various other details suggesting the possibility of the above interpretation could be cited, but this sketch of the pulsation argument will suffice for the present, since the purpose of the paper is not so much to advance an alternative theory as to question the validity of the spectroscopic binary hypothesis.

MOUNT WILSON SOLAR OBSERVATORY
August 13, 1914

[1] Cf. the hypothesis proposed by Schwarzschild as an alternative explanation of the change by six-tenths of a magnitude in the color index of η Aquilae (*Publikationen der v. Kuffnerschen Sternwarte*, **5**, C125, 1900).

THE RELATION BETWEEN THE WOLF-RAYET STARS AND THE PLANETARY NEBULAE[1]

By W. H. WRIGHT

The position of the Wolf-Rayet stars in the scheme of stellar classification has long been a matter of speculation by astronomers. In 1890, and again in 1891, Pickering drew attention to certain points of resemblance between their spectra and those of the nebulae, and classified both as belonging to a fifth type of stellar spectrum.[2] At about the same time (1890) Keeler, who was then engaged in his visual investigation of nebular spectra, independently announced his conviction that the nuclei of the planetary nebulae are closely related to the Wolf-Rayet stars.[3] Keeler's conclusion was based on spectroscopic evidence, but he does not make a categorical citation of the facts upon which his conclusion rests, and I have looked rather carefully through his published writings for light on this matter. There are, indeed, observations which might be regarded as in harmony with this view, but one is led by the inclusion of "other bright line stars" with those of the Wolf-Rayet type to hazard a guess that the deductions were perhaps of a general character. Still Keeler's belief in a close relation is so definitely asserted, not only in one, but in several publications, that few who knew that shrewd investigator's rare ability to say exactly what he meant can doubt that he was firmly convinced that some close relationship exists.

Four years later, in 1894, Campbell published the most exhaustive account of the spectra of the Wolf-Rayet stars that has yet appeared.[4] He observed all of the then known stars of this type which are within the reach of the instruments at Mount Hamilton. His observations were both photographic and visual, and covered

[1] Read before the Evanston meeting of the American Astronomical Society, August 1914.

[2] *Astronomische Nachrichten*, **127**, 1, 1891.

[3] *Publ. A.S.P.*, **2**, 279, 1890; also *Publ. Lick Observatory*, **3**, 227–228.

[4] *Astronomy and Astrophysics*, **13**, 448, 1894.

the spectrum from λ 4100 to H_α. He added numerous lines to the list of known ones, and, as most of these are of unknown origin, left the spectra even more enigmatic than he had found them. At about this time the same investigator made an equally comprehensive study of the spectra of the nebulae.[1] His conclusions as to a relationship between these two classes of spectra are therefore of the highest interest and, as expressed in his own words,[2] are as follows:

> Aside from the hydrogen, D_3, and 4472 lines, the nebular spectrum presents a few interesting coincidences with the Wolf-Rayet spectrum. The lines at 5412 and 4687 observed in several nebulae were found with more or less prominence in nearly all the Wolf-Rayet stars; but the lines at 4389, 4067, and 4026 were found in only a few of the stars, and it is not certain that the last two lines occupy the same positions in the nebulae and stars, though they probably do. The prominent star lines 5813, 5693, 5593, 5472, 4652, 4636, 4541, 4509, 4442 were specially searched for in the nebulae and not found. Likewise, the nebular lines 5751, 5007, 4959, 4715, 4364 were most carefully looked for in the stars, and no trace of them is visible. I think we must say that if any relation exists between these spectra, it is not clearly established and its nature is not apparent. . . . .
>
> In conclusion, I think we can say, from the foregoing observations, that the spectra of the Wolf-Rayet stars are not closely related to any other known type. They appear to have several points in common with the nebular and Orion-type spectra; but the last two appear to be much more closely related to each other than to the Wolf-Rayet spectra. It is therefore difficult to place these stars between the nebulae and Orion stars. They certainly do not come *after* the Orion stars, and one does not like to place them *before* the nebulae. We can probably say that the bright lines are chromospheric, owing their origin to very extensive and highly heated atmospheres, but showing very little relation, in constitution and physical condition, to that of our own sun. For the present, at least, this type of spectrum must be considered as distinct from every other known type, just as the nebular spectrum is distinct, and like the nebular spectrum containing lines whose origin cannot now be assigned.

I think that no one will question the justice of Campbell's conclusions, in the light of the great mass of evidence which he had brought to bear upon the subject. They seemed to set at rest the earlier notions that the connection between the two classes of objects was a close one.

[1] *Ibid.*, **13**, 384–494, 1894.

[2] *Ibid.*, **13**, 474, 1894.

Among the most interesting of the stars observed by Campbell is B.D.+30°3639. This he found to be surrounded by a glowing hydrogen envelope, and it is with this object that the present communication has, in part, to deal. It is hardly necessary to recount here the details of the discovery, as the remarkable observation on which it is based is familiar to everyone interested in the subject. This star is naturally an object of interest by reason of its peculiar appendage, and has perhaps been observed more than any other of its class. Palmer and Stebbins found the well-known nebular line λ 3727 in its spectrum,[1] but do not appear to have appreciated the significance of the discovery. The line was later reobserved by Wolf.[2] More recently Merrill has found the nebular lines λλ 6548 and 6583 in the spectrum of the star.[3]

A question at once suggested by the finding of nebular lines in the spectrum of this star is: Do they belong to the star proper or to the surrounding gaseous envelope? A careful examination of the material furnished by the foregoing observations discloses no evidence on this point.

The writer became actively interested in the problem through the following circumstance. In making a long exposure on the planetary nebula Struve 6=N.G.C. 6572 with a spectrograph attached to the 36-inch refractor, the following of the telescope was sufficiently good to isolate the spectrum of the nucleus as a narrow band of continuous spectrum cutting across the centers of the bright nebular lines, and in this band the line λ 4686 appeared, not as a narrow line, but as a band some 17 A wide.[4] The line in question does not appear in the outlying parts of the nebula. This appearance was so suggestive that the spectrum of the nucleus was of a Wolf-Rayet character that another exposure of 14 hours, running through two consecutive nights, was undertaken. The second exposure confirmed the first and showed in addition to other nucleus lines a faint broad emission band at λ 4057. The investi-

[1] *Lick Observatory Bulletin*, **2**, 53, 1902.

[2] *Sitz. Heidelberger Akad. Wiss.*, **14**, 1913.

[3] *Lick Observatory Bulletin*, **7**, 129, 1913.

[4] The nucleus of this nebula is not a stellar point, but consists of a thickening of the nebulosity close to the center. Nebular nuclei differ in this respect, some, for instance that of N.G.C. 6826, present in the telescope the appearance of stars.

gation was extended to the visible region by a two-night exposure with a bathed plate. The spectrogram shows a faint broad nucleus band at λ 5807. All the plates show numerous narrow lines extending to the outer limits of the nebula, and a few hazy ones restricted to the vicinity of the center. The three bands already mentioned, λλ 4057, 4687, and 5807, are the only really broad ones which are recorded. They are confined very closely to the center of the nebula. The most characteristic Wolf-Rayet bands are probably λλ 4057, 4687, 5694, and 5813. The agreement with the nucleus lines is in the first two cases exact. The third line is not shown in the nucleus spectrum, though a longer exposure might bring it out. The fourth band, λ 5813, varies in position in different stars from λ 5804 to λ 5817. It is in fact composite in the Wolf-Rayet star B.D.+30°3639, with components at λλ 5801, 5812, 5828. The nucleus line λ 5807, though uncertain, on account of the faintness of the image, is probably due to the blending of the first two components. The nucleus also exhibits the Wolf-Rayet bands λ 4633 and λ 4649 as hazy bright lines.

It will probably be admitted that the presence of the five bands λλ 4057, 4633, 4649, 4687, and 5807 establishes the nucleus of the nebula as a Wolf-Rayet star.

After settling this point it naturally became a matter of interest to inquire whether the so-called hydrogen envelope surrounding the Wolf-Rayet star B.D.+30°3639 is not in reality a true planetary nebula. If this were found to be so, the relation between the two classes of objects would appear to be quite a definite one. Observations were begun on the two red lines near H_α to determine whether or not they extend out into the nebula. The slit was adjusted to the focus of the large refractor for this region and the following was done as carefully as possible. The three lines λ 6548, H_α, and λ 6584 are sensibly of the same length, and correspond to an envelope diameter of 7 seconds of arc. Campbell's visual estimate of the diameter of the H_β image is 5 seconds. Since a visual measure of such a faint object might be too small, while the photographic record, on account of imperfect following and other disturbing factors must be too large, the agreement between the two results is satisfactory.

Exposures, each of two nights' duration, were then made covering respectively the visible and photographic regions of the spectrum. These plates show all of the brighter nebular lines, except λλ 3869, 4363, and the helium lines, to be present as narrow bright lines running out into the surrounding envelope. The observed lines include λλ 3726, 3729, 4069,[1] 4076, 4959 (N_2), 5007 (N_1), 5755, 6303,[2] 6548, 6583, and 6730 in addition to the 11 hydrogen lines from H_λ to H_α inclusive. This array is probably sufficient to give the so-called hydrogen envelope the status of a planetary nebula. A number of these lines will perhaps not be recognized, at once, as nebular radiations. They are all, however, in a list, which will shortly be published, of nebular lines observed by the writer. N_1 and N_2 are very faint and their lengths are not easily determined. They are undoubtedly much shorter than the hydrogen lines.

In two cases we have then a planetary nebula with a Wolf-Rayet nucleus. That this is not an exceptional condition is attested by a number of isolated observations made by members of the Lick Observatory staff, but heretofore unpublished. The observers have kindly accorded me permission to refer to their results in advance of their own announcements. A brief summary of these observations follows:

N.G.C. 6826: This nebula has a large, round, fairly bright disk. The nucleus is very bright. The line λ 4686 was found by Merrill to be localized as a hazy dot in the spectrum of the nucleus, and Dr. Paddock strongly suspects the well-known Wolf-Rayet band at λ 4650. The writer has also found the characteristic band λ 4057 in this nucleus spectrum. The visible spectrum has not been photographed. The nucleus is undoubtedly a Wolf-Rayet star.

[1] Since this paper was prepared my attention has been called to the fact that this line was observed as an envelope line by Adams about the year 1910 (*Science*, **32**, 882, 1910).

[2] This does not agree exactly with the nebular wave-length, which is λ 6301. In this object the line seems to broaden where it crosses the stellar spectrum, and may therefore be displaced to the red at this point in common with the stellar bands. In this region of the spectrum the prismatic dispersion is of course weak and the linear equivalent of the discrepancy is small.

N.G.C. Index 418=S.D.M.−12°1172: This is a particularly interesting nebula. According to Campbell the disks corresponding to N_1 and N_2 are smaller than the H_β disk.[1] The nucleus is a ninth-magnitude star. Paddock has found λλ 4686 and 4650 to be localized in the nucleus. The lines are rather narrow, and while the Wolf-Rayet character is not so pronounced as in other cases, the spectrum exhibits a strong tendency in that direction. λ 4057 is not present.

N.G.C. 40: This is a dim nebula with a central star. Paddock has found most of the stellar light to be concentrated in the Wolf-Rayet band at λ 4650.

These constitute all of the nebular nuclei of which the Lick Observatory has spectrograms. In every case the object is undoubtedly to be classified as a Wolf-Rayet star.

There seems to be no escaping the conclusion that the nuclei of planetary nebulae not only are closely related to Wolf-Rayet stars, as was first suggested by Keeler, but that in many cases they are such stars. Whether the converse proposition is true—that is, that those stars are in general the nuclei of planetary nebulae—cannot by any means be considered as having been established. One is in fact tempted to risk a guess that it is not. However, it is possible that further observations will shed some light on this, as well as on other aspects of the problem.

The observations already secured not only demonstrate the relationship which has been indicated between the nebulae and the stars, but are strongly suggestive of the nature of certain steps in the progression from one form to the other. Attention has already been called to the fact that the helium lines are absent from the nebulous envelope of the star B.D.+30°3639. They are, however, well represented in the star proper, where they occur as broad bands displaced an angstrom or two to the red of their normal positions. The lines N_1 and N_2 are probably shorter, as well as fainter, than the hydrogen lines. If we assume that by some process of evolution the nebula is condensing into the star, it is apparent that the order of settling is helium, "nebulium," hydrogen. There is considerable additional evidence favoring

[1] *Astronomy and Astrophysics*, 13, 494, 1894.

the view that this is a usual line of development, and the theory finds confirmation in the relative sizes of the disks in the planetary nebula S.D.M.$-12^{\circ}1172$. More observations are required, however, before the validity of this rule can be considered to be established.[1]

The foregoing is only a preliminary account of the observations already secured; a more detailed one will appear later. The need of a more complete investigation both of the Wolf-Rayet stars and of the planetary nebulae in the vicinity of their nuclei is indicated. Although the faintness of the objects renders the work both precarious and tedious the writer hopes to extend the range of the observations during the coming year.

MOUNT HAMILTON
August 1914

NOTE

Further observation strengthens the conclusion that the relationship between the Wolf-Rayet, or Class O stars, and the nuclei of the planetary nebulae is a very close one. The extra series of dark lines found by Pickering in the spectrum of ζ Puppis are of rather common occurrence, as absorption lines, in the spectra of the nuclei; in fact the resemblance to the spectrum of ζ Puppis is, in many cases, very strong. In at least one instance, the nucleus of the beautiful planetary in Geminorum, N.G.C. 2392=G.C. 1535, the hydrogen and helium lines, as well as the members of the Pickering series, are dark. The spectrum is that of a Class Oe star. Hydrogen is represented by comparatively weak emission lines in the nebula proper.

November 1914

[1] Strictly speaking, evidence of this nature, even if amply confirmed, could only be taken to *prove* the settling of the lines, or say the conditions favorable to radiations of a certain character. For instance the line λ 4686 becomes localized in the nucleus before either the hydrogen series or the helium lines, yet it probably belongs to one or the other of the elements in question, perhaps to hydrogen. The phenomenon is of course analogous to the local occurrence of lines in terrestrial sources.

ON SYSTEMATIC ERRORS OF STELLAR RADIAL VELOCITIES

By SEBASTIAN ALBRECHT

Ever since it was found that the wave-lengths of numerous lines in stellar spectra vary progressively as a function of the spectral types of stars,[1] the writer has, on various occasions, suggested that it is extremely likely that a large share of the systematic differences in radial velocity results is due to the wave-lengths used in the reductions. This applies to the relative radial velocities for the different types as determined at any one observatory, and especially to the systematic differences between radial velocities for each type considered separately as determined at the different observatories. The recent publication by Küstner[2] of a second list of radial velocities and the wave-lengths upon which they are based makes possible an approximate test of an effect of the second kind referred to above.

The basis of this test will be a comparison, separately for each stellar spectral type, of Küstner's wave-lengths with the writer's preliminary wave-lengths as published in *Boletín No. 1* of the Córdoba Observatory. Use will also be made of the systematic differences which Küstner finds between his radial velocities and those of the Lick Observatory.

Table I is self-explanatory. For present purposes it is inadvisable to assign different weights to individual lines in forming the means at the bottom of this table, nor is it necessary to make a detailed study of each line (or blend), as must be done later in a definitive discussion of this problem. Such study would possibly have resulted in the exclusion of a few lines from the table, principally on account of differences in dispersion.[3] The large number

[1] *Lick Observatory Bulletin*, No. 106; *Astrophysical Journal*, **24**, 333, 1906.

[2] *Astronomische Nachrichten*, No. 4750, 409, 1914.

[3] The majority of the Lick radial velocities are based upon plates taken with three-prism spectrographs, with a considerable range in the dispersions used. The Bonn spectrograms are also taken with a three-prism spectrograph but with smaller dispersion. In the Bonn second series the dispersion is only about one-third that of the Lick plates, while in the Bonn first series the dispersion was double that of the second series.

TABLE I

DIFFERENCES IN WAVE-LENGTH (ALBRECHT—BONN)

λ \ Type	F5	G	G5	K	K5	Ma	Mb
	A						
4236.1	−.021	−.021	−.021	−.021	−.021	−.021	−.021
42.7	−.070	.....	.....	.....	.....	.....	.....
45.4	+.008	+.008	+.008	+.008	+.008	+.008	+.008
46.9	−.077	−.034	+.019	+.013	+.006	+.001	−.002
50.2	+.006	+.006	+.006	+.006	+.006	+.006	+.006
50.9	+.005	+.005	+.005	+.005	+.005	+.005	+.005
54.5	−.006	+.032	+.030	+.028	.....	.....	.....
58.4	.....	.....	.....	−.006	+.006	+.008	+.008
60.6	+.113	+.128	+.152	+.182	.....	.....	.....
74.9	+.002	−.005	−.009	−.010	.....	.....	.....
86.1	.....	.....	.....	−.024	+.039	+.047	+.067
88.1	−.008	+.013	+.027	+.036	(+.181)*	.....	.....
93.2	.....	−.016	+.001	+.018	+.036	.....	.....
94.2	+.007	+.007	+.007	+.007	+.007	+.007	+.007
4313.0	+.049	+.043	+.088	+.083	+.100	+.099	+.098
14.3	+.011	+.019	+.059	+.051	+.034	.....	.....
15.1	+.056	+.046	+.034	+.021	+.007	−.005	−.010
18.8	+.030	+.044	+.056	+.062	+.062	+.057	+.054
21.0	−.008	+.005	+.028	.000	−.028	.....	.....
34.0	.....	+.007	+.033	+.050	+.061	+.066	+.068
39.7	.....	+.043	+.043	+.043	+.043	+.043	+.043
40.6	−.001	−.002	−.070	−.082	(−.191	−.220	−.240) †
44.5	−.050	−.024	.000	+.021	+.038	+.052	+.057
52.9	−.014	−.003	+.009	+.025	+.042	+.057	+.066
66.7	.....	+.090	+.048	+.005	−.045	.....	.....
76.1	−.006	−.006	+.084	+.084	+.084	+.084	+.084
79.3	.....	+.023	+.023	+.023	+.023	+.023	+.023
83.7	+.051	+.051	+.051	+.051	+.051	+.051	+.051
91.9	.....	.....	−.006	+.017	+.045	+.075	+.092
95.2	−.076	−.065	−.054	−.044	−.031	−.015	−.005
4401.6	+.063	+.063	+.063	+.063	+.063	+.063	.....
04.9	+.022	+.022	+.042	+.052	+.072	+.072	.....
12.2	+.021	+.060	−.015	+.017	+.044	+.062	+.069
25.6	−.145	−.100	.....	+.022	+.047	+.057	.....
27.4	−.031	−.037	+.008	+.002	−.002	−.006	−.008
59.3	−.048	−.033	−.026	−.023	−.022	.....	.....
64.7	−.083	−.019	+.025	+.055	+.078	.....	.....
66.7	−.027	−.021	−.007	+.009	+.018	+.019	+.019
68.6	−.009	.000	+.014	+.035	+.055	+.068	+.073
69.5	−.084	−.050	−.017	+.013	+.043	.....	.....
73.0	+.080	+.022	+.020	+.040	−.010	−.061	−.085
82.4	.....	−.026	−.025	−.027	−.048	−.081	−.105
94.7	+.044	+.044	+.044	+.044	+.044	.....	.....
4522.8	−.003	+.011	−.015	−.020	+.024	−.052	.....
28.8	−.016	.000	+.010	+.015	+.016	+.017	+.017
31.2	.....	−.010	−.007	+.003	+.034	+.065	+.084
34.1	+.020	+.016	+.009	+.005	+.001	.....	.....
49.7	−.044	−.027	−.013	+.003	+.017	+.030	+.036

*Omitted because it is used only 7 times by Küstner and therefore would influence these results unduly if included.

†Omitted because it is used only 4 times by Küstner and therefore would influence these results unduly if included.

TABLE I—*Continued*

A \ Type	F5	G	G5	K	K5	Ma	Mb
	A						
4565.7	.....	.....	−.010	−.016	−.023	−.029	−.031
80.3	.....	.....	.....	−.005	+.005	.....	.....
86.1	.....	−.007	+.050	+.001	+.025	+.035	+.038
4603.1	.....	.....	.....	.....	+.016	.....	.....
	A						
Means	−.0063	+.0067	+.0174	+.0188	+.0225	+.0260	+.0260
No. of lines	38	45	46	50	46	35	31
Equivalent difference in radial velocity	km +0.43	−0.46	−1.19	−1.29	−1.60	−1.77	−1.77

of lines used (53) gives ample reliability to the main result, namely, that the systematic differences in the radial velocities of Lick and Bonn are largely (and perhaps nearly entirely) due to differences in the wave-lengths which were employed for the lines used in the reductions.

Directly below the means of $\Delta\lambda$ in Table I are given the equivalent systematic differences in the radial velocities, in the sense (Albrecht−Bonn), which would result from the use of the two sets of wave-lengths respectively.

TABLE II

SYSTEMATIC DIFFERENCES IN RADIAL VELOCITIES

Type	(*a*) Küstner's Observed (Lick−Bonn)	(*b*) Küstner's Adopted (Lick−Bonn)	(*c*) Ludendorff, for Bonn First Series (Lick−Bonn)	(*d*) Due to Wave-Lengths Used (from Table I) (Albrecht−Bonn)	No. of Lines on Which (*d*) Is Based
	km	km	km	km	
F5	+0.23	0.0	0.0	+0.43	38
G	+0.15	0.0	−0.6	−0.46	45
G5	−1.06	−1.0		−1.19	46
K	−1.42	−1.4	−1.1	−1.29	50
K5	−2.30	−2.3		−1.60	46
M	−2.78	−2.8	−2.4	−1.77	35

Table II gives a comparison of: (*a*) Küstner's observed mean differences (Lick−Bonn); (*b*) Küstner's adopted differences (Lick−Bonn); and (*d*) the differences (Albrecht−Bonn) with the number of lines upon which the values in (*d*) are based.

The similarity between columns (*a*), (*b*), and (*d*) seems quite convincing. In fact, from types F5 to K they are nearly identical. The smaller value of (Albrecht−Bonn) in the M type is due without much doubt to one or more of the following causes: (1) the list of lines in Table I[1] does not constitute the complete list upon which the radial velocities are based; (2) for the reduction of each individual spectrogram only a small fraction of the total list of lines is employed, and it is therefore practically certain that the different individual lines have been used very unequal numbers of times in both the Bonn and Lick results; (3) though the writer's wave-lengths—upon which the comparison rests—are based entirely upon measures of Lick spectrograms, there may readily be a small systematic difference between this system and the average for all the reductions of M-type stars in the Lick results.

In column (*c*) of Table II have been added the results of Ludendorff,[2] who has found similar systematic differences between Lick and Bonn for Küstner's first list of radial velocities. Whether the results for the first list may be looked upon as additional evidence, supplementary to the more definite evidence from the second list, cannot be decided with certainty without recourse to the wave-lengths used in the reduction of the first list, which were not published. However, it seems likely that the accordance is not accidental, but that the systems of wave-lengths of the two lists are approximately the same in a systematic sense, for the ordinary method of determining relative wave-lengths in the different spectral types by means of residuals leaves *the system as a whole* nearly unchanged.

The question as to the proper distribution of these systematic differences between the two observatories need not be considered here in detail. Küstner finds that his check plates (of type between G and G5) give a systematic correction of −1.06 km, which must be very close to the exact amount required to bring the Bonn radial velocities for this type into coincidence with those from the Lick. As far as the evidence in Table II goes, it indicates that each of

[1] Only my list of lines published in the article referred to is being used in this comparison.

[2] *Astronomische Nachrichten*, No. 4705, 1, 1913.

these two observatories has succeeded in large measure in freeing its radial velocities for stars of the sun (G+) type from systematic error.

The comparison of Küstner's radial velocities with those of the Lick Observatory refers only to types F5 to M. For the earlier type stars attention has already been called, in former notes,[1] to the great uncertainty in the radial velocities on account of the presence in them of systematic errors of (at present) unknown amount, due to the considerable uncertainties as to the correct wave-lengths to be used for the lines which must be employed in determining these radial velocities. In the first of the two references quoted it was shown that the only two available good determinations with high dispersion of the wave-lengths of the three important silicon lines λ 4552.7, λ 4567.9, and λ 4574.9 differ from each other systematically by 0.090 A, corresponding to a systematic difference in the radial velocity obtained from them of 6.0 km. In the laboratory spectra the lines are generally somewhat diffuse and seem to be sensitive to the atmosphere surrounding the spark. As far as the writer is aware, no further laboratory investigations of these lines have been made, and he wishes again to call attention to the importance of, and the need for, a definitive study of them in the laboratory, under a variety of different conditions.

The systematic errors in stellar radial velocities which are discussed above are independent of, and in addition to, other and at present almost entirely unknown systematic errors for which the source of error lies chiefly in the stars themselves, such as pressure and radial motions in the atmospheres. In this connection it may be well to refer to Campbell's[2] inference, based on the recent work of Evershed on the sun, of rapid convection (radial motions) in stellar atmospheres as the source of the systematic differences which he found in the radial velocities for the different stellar spectral types, and which he designated by the letter *K*.

[1] *Publications of the Astronomical and Astrophysical Society of America*, **2**, 71, 1911; *ibid.*, 73.

[2] *Lick Observatory Bulletin*, No. 257, p. 82, 1914.

In Table III are given approximate values of Campbell's *K*-term.[1] These are seen to be of the same order of magnitude as the quantities in Table II, which latter have been shown to be due to differences in the assumed wave-lengths. Nothing in Table III is in itself contradictory to the extreme view that the *K*-term may have its source entirely in the adopted wave-lengths. On the other hand, Campbell's suggestion involves some difficulties, though these may not be insurmountable. Perhaps the most serious difficulty, in our present state of knowledge, would be to explain, on the basis of convectional currents in the atmospheres, the large value of the *K*-term in the M-type (see Table III). It

TABLE III

Type	Campbell's *K*-Term
B	+4.0±km
A	+1.0
F	+0.1
G	±0.0
K	+2.0
M	+4.0

does not seem likely that in the M-type stars, which are presumably quite viscous and sluggish in comparison with the B-type stars, the radial convection in the atmosphere should be as rapid as in the B-type stars. It might be well, however, to bear in mind that the final reductions are likely to alter quite materially the values of the *K*-term in the different types, and that this difficulty may then disappear. That radial movements do occur in the stellar atmospheres is the direct inference from the recent work on the sun. Besides Evershed's work, St. John has shown radial motion for Ca vapor[2] and Perot and Lindstreedt[3] for H, Mg, and Na. The extent to which these radial movements are involved in the stars is a problem for the future.

As the writer has pointed out before, up to the present no adequate attempt has been made by the use of carefully studied systems of wave-lengths to avoid introducing in the radial velocities

[1] *Op. cit.*, No. 196, p. 127, 1911.

[2] *Astrophysical Journal*, **32**, 36, 1910.

[3] *Comptes rendus*, **152**, 1367, 1911; **154**, 326, 1912.

just such systematic errors as would result in a K-term. Until this has been done we cannot escape the inference that at least part of this term, and possibly the major part, may be due to systematic errors of this kind. The problem is complicated in some respects by the fact that a large percentage[1] of the lines in stellar spectra have different wave-lengths in the different spectral types. In other respects, however, the fact that these variations are *progressive* as a function of the spectral type places in our hands an additional tool. Those lines which are of constant wave-length over a considerable range of spectral type promise to be the most important connecting links between the types, though additional adjustment may also be required.

In another connection the writer has been engaged in the determination of standards of wave-length for each stellar spectral type. These systems must be upon a fundamental basis as far as possible, and though—perhaps contrary to the general impression among astrophysicists—the laboratory wave-lengths are at present not as satisfactory for this purpose as could be desired, the writer believes that his systems will be sufficiently close approximations for present needs. For this reason it seems best to defer to a later date an attempt to separate from the K-term the portion which is due to the use of erroneous wave-lengths (erroneous for each type considered separately) from the portion that may be due to causes within the stars themselves.

SUMMARY

Stellar radial velocities are known to contain systematic errors. These may be separated into two divisions: (*a*) systematic differences between the results for the same stars as observed at different observatories, and (*b*) systematic differences dependent upon the stellar spectral type, which were found by Campbell and designated by the letter K. The former must clearly be due to causes within

[1] In *Córdoba Observatory Bulletin*, No. 1, in the region of spectrum covered and for types A to M, an average of one line per 3.5 angstroms was found for which the wave-length varies as a function of the stellar spectral type. In the B-types the problem is more difficult, but here also several lines were found in 1907 and 1911 (not yet published) which seem definitely to vary in wave-length as we proceed from the early to the late B-types.

the control of the observer, i.e., the instruments and the methods of measurement and reduction of the spectrograms. The latter are due in part to these same causes, though they may—and probably do—depend also upon causes within the stars themselves.

Owing to the great perfection of modern stellar spectrographs, errors from instrumental sources must be nearly, if not entirely, negligible. The writer has previously shown: (1) that a large percentage of the spectrum lines vary in wave-length progressively as a function of the stellar spectral type; (2) that for many of the lines—and these must be used in determining the stellar radial velocities—the laboratory values of the wave-lengths are not sufficiently accurate to meet the requirements of the radial-velocity observer. This leads unavoidably to the inference that the systematic differences in the radial velocities under division (*a*) above are due in major part, if not entirely, to the adoption by different observers of different wave-lengths for the same lines. A discussion of the systematic differences between the radial velocities as determined at the Lick and Bonn observatories shows this to be true for these two observatories.

From (1) and (2) in the preceding paragraph it is evident that the systematic errors K, dependent upon stellar type, will require revision. At present it is not feasible to separate from the K-term the portion that is due to the use of erroneous wave-lengths from the portion that may be due to causes within the stars themselves. In another connection the writer has been engaged in the determination of standards of wave-length for each stellar spectral type. When these are completed it will be possible to attempt this separation.

DUDLEY OBSERVATORY
ALBANY, N.Y.
September 24, 1914

Minor Contributions and Notes

A SIMPLE METHOD FOR DETERMINING THE AMOUNT OF LIGHT LOST IN A STELLAR SPECTROGRAPH

The proportion of light lost in a spectrograph may be determined photographically by comparing the exposure time necessary to produce an ordinary trail at the focus, of the same length, width, and density as that of the spectrum, with the exposure time of the spectrum, for the same star.

Owing to the great disparity in the times required to produce a trail and a spectrum of the same star with the same telescope, the trail should be very much widened and this difference of width allowed for. Usually bright stars are to be preferred for such experiments as the foregoing.

As the spectrum will not be of uniform density, its average should be determined by measures at a number of points.

It is hardly necessary to point out that the same emulsion of dry plates should be used for both spectrum and ordinary trail and that care should be exercised that the development is exactly alike, either by development together in the same bath or by means of standard squares from a reliable light-source, or, better still, by making exposures on the same plate where possible.

Comparisons may be made for different dry plates and for different parts of the spectrum.

It would also be of value to determine the loss for different widths of slit and qualities of "seeing." This latter would be of especial interest in the case of very large telescopes and would, I think, disclose great losses due solely to the spreading of the disk over a comparatively large area by atmospheric disturbances and by the bodily wanderings of the image from the slit due to instrumental and atmospheric causes.

To make certain of getting all of the starlight through the spectrograph for the case in which this condition is desired, the slit should be opened very wide.

The simple comparison of loss of light for different slit-widths would be of interest as compared with the total light falling on the slit-plates, and should be made as a part of such an investigation as suggested.

Although especially developed for spectrographs used in stellar work, the above method is applicable to determining the loss where surfaces are dealt with.

This method is also suitable for use with all forms of slitless instruments.

C. D. PERRINE

OBSERVATORIO NACIONAL ARGENTINO
CÓRDOBA
May 16, 1914

Reviews

Die veränderlichen Sterne. Erster Band: Geschichtlich-Technischer Teil. Von Johann Georg Hagen, S.J. Erste Lieferung: "Die Ausrüstung des Beobachters." Freiburg: Herdersche Verlagshandlung, 1913. 4to, pp. xv+152. M. 10.

The pressing need of a comprehensive work on variable stars has been long felt, but the accelerated speed of discovery and the diversity of methods used in the last few years have made the need even more urgent. No branch of astronomy is so attractive to amateurs and none has been so dependent on amateurs for observational data, but the available variable star material has been scattered among periodicals and fragmentary publications largely inaccessible even to the average professional astronomer, and beyond the reach of most amateurs. If the author had done nothing more than to collect the bibliography given on pp. ix–xv, he would be entitled to our gratitude; but in addition he has assorted, arranged, and condensed this rich material with a skill and ripe judgment which could come only from a lifetime devoted largely to this branch of astronomy, and evidenced by his previously published works, for example, the unrivaled *Atlas Stellarum Variabilium*.

The old epoch of exclusively visual observations ended with the application of photographic and spectroscopic methods, especially to the discovery of variable stars; and while there is no immediate prospect of the eye being superseded by the prism and plate, it is no longer the only or even the main reliance. It is therefore fitting that the history of visual methods and results should be written at this time. The present work is therefore distinguished by the demand, its timeliness, and the quality of its execution.

The whole work is planned to appear in two volumes, of which the second, dealing with the physical explanation of the phenomena of variability, will be written by Father J. Stein. The present "historical-technical" volume is to appear in the following four parts: (I) "The Equipment of the Observer"; (II) "Methods of Observation"; (III) "Reduction of the Observation"; (IV) "Elements of the Light-Changes." The forthcoming publication of the great catalogue of variable stars, which has taken so much of the time of the Commission of the Astronomische Gesellschaft for the past thirteen years, will find

a fitting supplement in this more general work, though Part IV will apparently overlap the Gesellschaft catalogue. Taken together, these two works will cover the variable star field with great thoroughness, and will seem to secure for the Germans the lead in the literature of this branch of the science.

The present work is intended as a "source book," for which each reference has been verified with great care, and given (usually in its original language) in sufficient detail to make the meaning clear. For this reason the author does not consider the work a proper subject for translation, but believes rather that it should serve as a basis for manuals in the different languages.

Only one who has tried to keep track of the literature scattered through so many periodicals can fully appreciate the wealth of material collected in the introduction and five chapters, as evidenced by a bare list of subjects: the beginnings and meaning of the theory of variation; methods of observation; history of the study of variables; publication of observations and results; the visible signs of variation; classification, number, and distribution of variables; catalogue, nomenclature, and alphabetical lists; instruments, charts, ephemerides, and directions for their use; observing program for known, recently discovered, and suspected variables; co-operation in observation.

Without attempting to mention all the notable features of the work, the following points deserve special mention: (1) the table on p. 56 comparing seven of the principal classifications proposed or in use; (2) the table on p. 62 showing the distribution with reference to the galaxy of the faint variables, the bright variables, the Algol-type, and the Novae; (3) the table on p. 68 giving the principal catalogues of variables; (4) the comparison of different systems of nomenclature given on p. 84; (5) the advice given in chap. v on the preparation of an observing program, so much needed in view of the recent enormous increase in number of known variables.

The point of view of the author is mainly historic, as shown by the statement on p. 5: "Visual observations without the aid of photometers or colorimeters will have especial attention, as they form the historic methods and have not yet been comprehensively treated." The few criticisms which might be made have to do mainly with astrophysical subjects.

1. The statement on p. 6 in regard to the greater range of the photographic, as compared with the visual light-curves of certain variables is correct; but that implies a change in color, i.e., the variable is redder

near minimum. This is inconsistent with the statement on p. 30 that stars varying in color have not yet been discovered.

2. On p. 143, referring to "short-period" variables, the author says "their spectra appear to lie chiefly between the types Oe5 and B9"; but the table on p. 56 shows that most "short-period" variables are of the ζ Geminorum or δ Cephei types, of which the spectra are usually of Harvard Class G. It seems probable that the author means to refer to the Algol-type variables.

3. The statement on p. 34 that most modern Novae have been identified with previously existing stars seems open to question.

4. On p. 41 the author states that "small departures [from regularity of period] up to 10 per cent occur with all variables." Does this apply to the Algol and δ Cephei types?

5. The statement is made on pp. 56–57 that "knowledge of the inner mechanics of variables is disclosed only by spectrum analysis." The discovery of color-changes might be added to the sources of such knowledge.

6. The omission of the highly valuable observation of Yendell from the list on p. xv should be noticed.

7. The lack of an index will doubtless be supplied in the later parts of the volume.

The best proof of the usefulness of a book is the use that is made of it. This book has already been drawn upon as a source by Kempf in his fifth edition of Newcomb-Engelmann's *Populäre Astronomie*, and by Hartwig in his "1914 Ephemeris of Variable Stars" in the *Vierteljahrsschrift*.

The format, 9×12 inches, is inconveniently large and is not required by any tabular matter in this part, but may be needed in later parts. The type and presswork are extremely good, and the price, $2.70 net, is low. American purchasers can secure copies from Herder's St. Louis branch, at 17 South Broadway.

J. A. PARKHURST

YERKES OBSERVATORY
WILLIAMS BAY, WIS.

Beyond the Atom. By JOHN COX. Cambridge Press, 1913. 12mo, pp. i+146. $0.40.

This is a charming little primer on radio-activity written by one who is at the same time a physicist, a philosopher, and a literary artist. The two most delightful chapters are the first, which deals with the growth

of physical ideas from 1800 to 1890, and the last, which presents the necessarily vague and impressionistic picture of the "new atom" and its relations to the physical world. The material between these two chapters is divided into seven others and represents largely an abridgment and restatement in most readable form of the content of Rutherford's *Radio-Active Substances and Their Radiations*. I know of no better short treatment of the subject for the non-technical reader. It is both reliable and interesting. The only defect is a certain lack of up-to-dateness shown in the inclusion of some old values of constants and in the omission, though published in 1913, of the epoch-making work of Laue and his co-workers, published in 1912. In view, however, of the rapidity with which new points of view chase one another across the stage of modern physics, it is scarcely possible even for the actors to get a wholly correct view of the present situation, and a *book* must necessarily depict an act which is past rather than the one which is passing.

R. A. MILLIKAN

UNIVERSITY OF CHICAGO
May 11, 1914

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

Articles written in any language may be accepted for publication, but unless a wish to the contrary is expressed by the author, they usually will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts typewritten, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

All drawings should be carefully made with India ink on stiff paper, usually each on a separate sheet, on about double the scale of the engraving desired. Lettering of diagrams will be done in type around the margins of the cut where feasible. Otherwise printed letters should be put in lightly with pencil, to be later impressed with type at the editorial office, or should be pasted on the drawing where required.

Where unusual expense is involved in the publication of an article, either on account of length, tabular matter, or illustrations, arrangements are made whereby the expense is shared by the author or by the institution which he represents.

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Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

If a request is sent *with the manuscript*, one hundred reprint copies of each major article, bound in covers, will be furnished free of charge to the author. Additional copies may be obtained at cost price. No reprints can be sent unless a request for them is received before the JOURNAL goes to press.

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ERRATA

Vol. **39,** May 1914, in Professor Grabowski's article "On the Theoretical Photometry of Diffuse Reflection":

Page 299, line 20, *cancel* diffuse scattering or.

" 299, " 25, *for* This value is, *read* The value of J for this direction is.

Page 302, line 15, *for* The, *read* Thus, the.

" 303, lines 7, and 20, *for* $\sqrt{1-s^2 \cdot a^2}$ *read* $\sqrt{1-s^2\alpha^2}$.

" 303, line 8, *for* illumination, *read* the emanating radiation.

" 305, " 1, *for* the first, *read* also the first.

" 305, " 30, on the right margin add the designation (*b*) of the equation.

Page 306, lines 15 and 27, *for* normals to the mirror, *read* normals of mirrors.

Page 306, line 26, *after* element *add* of the body.

Vol. **39,** May 1914, in the article by Adams and Kohlschütter, on "The Radial Velocities of One Hundred Stars with Measured Parallaxes":

Page 349, line 15, *for* $0''.01$, *read* $0''.10$.

Vol. **39,** June 1914, in Professor Barnard's article on "Visual Observations of Halley's Comet in 1910":

Opposite page 380, Plate VIII, middle photograph, *for* $18^h.5$, *read* $20^h.1$.

Vol. **40,** July 1914, in Professor Plaskett's article on "Improvements in the Optical System of the Stellar Spectograph":

Page 133, heading of Table IV, *for* exponents, *read* exposures.

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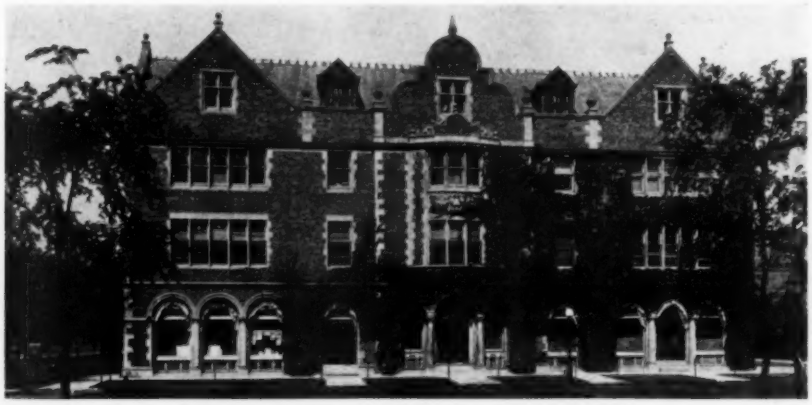

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